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THE PRINCIPLES OF PHYSICAL GEOLOGY

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PREFACE



With many excellent textbooks on the principles of geology already available to college students, the writing of another book in this field may seem to require explanation. It is supposed that the widespread advances in our knowledge of the earth may well serve as a minimum justification for the production of a new book; yet it is recognized that a new book cannot be expected to realize its full possibilities for usefulness unless in addition its objectives are cast in terms of the present needs of its readers.

During the writing of this book the authors have kept in mind the requirements of two groups. It is intended, first of all, as a help to those who seek to find greater pleasure in their surroundings, both immediate and distant. It is hoped that they may find through this book a way to a greater enjoyment of the land in which they live and of any which they may visit, as well as an understanding of lands which they may never see at all. Therefore every effort has been made to make the subject matter of the book as concrete as possible and to place emphasis upon the topographic effects of geological processes, both those which are revealed in the grand scenery of the present day and those which appear in less spectacular features of only everyday interest.

Second, the content selected and the structure established for this text have resulted from a belief as to the basic importance of physical geology to those students who will pursue advanced work in geology. Experience in the classroom should convince anyone of the disadvantage at which a student finds himself who has had only a superficial contact with the principles underlying this phase of the science. The student undertaking advanced work who has not acquired a thorough familiarity with the characteristic effects of the various geological agents has a poor foundation for any sort of field work or for specialization in the various branches of geology. For this reason, considerably more attention has been given to the description of geological effects as they appear in the field than is usual in most books of this kind. Less attention has been accorded theoretical matters, such as the hypothetical condition of the earth's interior and the theory of isostasy; these are subjects of interest,

but they can be mastered later in a student's career without prejudice to the success of his work as a whole.

It was also believed that the beginning student would probably secure a firmer grip on his study of the earth if he were early introduced to the field methods upon which geological knowledge depends. Accepting scientific statements on faith, with little or no idea of how they are substantiated, is not a satisfying experience for the intelligent student. For this reason a section on methods of geological study in the field has been introduced.

A departure from the usual method of presentation has been the use of topographic maps to illustrate various topographic features. In the Appendix the sections of a number of topographic maps have been included. These have been selected for their usefulness in illustrating points of geological interest. Use of these maps will show that many topographic features, especially those covering a large area, can be demonstrated to much better advantage on topographic maps than by photographs or diagrams. The student will see the application of these maps better when his introduction to them follows closely the textbook work, rather than when they are studied only as a separate laboratory project. References to the maps are therefore closely integrated with the study of physiographic forms and geological processes. A brief discussion of topographic maps and their interpretation is also included.

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**THE PRINCIPLES
OF PHYSICAL GEOLOGY**



Official United States Air Forces Photograph

The canyon of the Colorado River is a young valley; it is a mere notch cut out of a vast plateau. Its vertical lines call attention to arid climate and high elevation.

I • GEOLOGY, ITS MEANING AND METHODS



Geology is a very young science. Even its name was coined only as recently as 1778.

The nature and significance of fossils, it is true, had been recognized more than five hundred years before the birth of Christ, and Aristotle (about 325 B.C.) had known, among other geological facts, that the rocks of the earth participate in slow vertical movements. Nevertheless, despite these and other random contributions of later ages, the growth of a reliable knowledge of the earth has been slow and painful, beset by confusion and conjecture on the one side, and by prejudice and even persecution upon the other.

Not the least of the stumbling blocks in the path of the establishment of geology upon a scientific basis was the inability of men to comprehend the vastness of geological time. This difficulty is well illustrated by the solemn pronouncement of the Reverend James Usher, the scholarly archbishop of Armagh, in the seventeenth century, relative to the date of creation, which he set at 4004 B.C., on the 23d of October, at nine o'clock in the morning! While few would vie with the erudite doctor in regard to such exactitude of detail, the overwhelming majority of the people of his time concurred in his belief that the history of the earth was to be encompassed within the span of some six thousand years.

Such a view had of course a strangling effect upon scientific generalizations as to the nature of the geological processes. That the earth had been through tremendous adventures and had seen mighty changes during its obscure past was plainly evident to every inquiring eye; but to concentrate these changes into a few brief millennia required a tailor-made philosophy, a philosophy whose basis was sudden and violent change. The earth, it was accordingly assumed, had been subject to repeated convulsions, or catastrophes. Mountains, whole continents even, were thought to have been brought into being or destroyed or submerged beneath the waters of the sea during revolutionary up-

heavals, sometimes of such scope as to involve the whole globe. Great canyons were interpreted, not as the products of incomprehensibly slow river wear, but as cracks or rips in the earth's crust. Life was supposed, at least in some instances, to have suffered annihilation during these catastrophes, and to have been created anew when the trouble was over.

It is hardly surprising that the rocks and their fossils were misunderstood, or that scientists found little incentive in the prevailing philosophy of the day for prying into the secrets of the earth's past. It was not until James Hutton, a Scottish physician of the middle eighteenth century, called into question this doctrine of violent cataclysms that geology began to take on a truly scientific aspect.

To Hutton, more than to any other, belongs the credit of opening up the great vistas of time so necessary to an intelligent interpretation of geological history. Hutton traveled widely over the British Isles, studying rocks and their structures. He found sandstones, mudstones, and "pudding stones" to be made of just such fragments as were then being washed into the sea by rivers, or ground from the shore by sea waves, later to be sorted and reassembled into rock. He observed in the rocks both ripple marks and sun cracks, and noted their similarity to the markings even then in process of formation along the shore. He discovered shells in the rocks, and found their counterparts among the living creatures that inhabited the shallow water. To Hutton these observations spoke no word of sudden, violent convulsion, but rather of the same quiet, orderly change that goes on in nature all the time. To him they suggested "no vestige of a beginning, no prospect of an end."

Hutton's conception of the uniformity of nature is considered to mark the beginning of the modern era of geology. "What more can we require?" he asked in connection with the crumbling remains of great mountains. "Nothing but time." With time—abundant, endless time at their disposal, geologists found no need to call upon extraordinary forces to explain the earth; they needed only time, and the feeble strength of wind and stream and weather. And with such a viewpoint came the possibility of piecing together the puzzle of the earth's past, of tracing its history backward, not as far as the most recent cataclysm, but to a point very near to its beginning.

GEOLOGY AS A MODERN SCIENCE

Reading the past by studying the present. Logically, then, an introduction to earth science should start with a study of those geological processes that are acting upon the earth at the present time. In this volume we shall examine the building bricks of matter, and study the manner of their association into the minerals and rocks of geology. We shall trace the history of these materials, their wasting away under the attacks of air and water, their erosion and transportation by streams, wind, and ice, their assortment in the ocean and reassembly into rock. We shall follow the fate of rock as it is affected by bending and fracturing, heat and pressure; and in this way we shall become familiar with the forces that shape the landscape, control the volcano and the earthquake, and cause the majestic rise of mountains out of the sea.

When the student learns that he himself can see the differences between the pebble that has been rounded by the action of water and and that which bears the marks impressed by glacial ice, or that which has been sanded down for ages by the wind, he realizes, perhaps for the first time, that these same differences are the key to conditions of the ancient past. When he learns that he himself, with only a little practice, can read many of the marks of old shore lines, that he can identify rocks that were once the sands of prehistoric deserts, or that he can recognize at a glance glacial deposits or regions that have suffered glaciation, he not only finds far more of interest and significance in the rocks about him, but he is then ready to take up with confidence and understanding the fascinating problem of the earth's colorful history.

Scope and subdivisions of modern geology. Since the time of Hutton other men of genius have bent their efforts toward a better understanding of the earth, and, in spite of its comparative youth, the science of geology has scored impressive advances. As in other sciences, specialization is necessary if one is to go very deeply into the subject. The study of the earth in general and of the processes acting upon it from within and without is called physical geology, and that dealing with the changes it has undergone and the past life upon it, historical geology. Economic geology is the study of the occurrence and characteristics of valuable mineral deposits, and it includes a number of

important subdivisions. Petrology is the study of the rocks of the earth, and mineralogy the study of minerals. Stratigraphy involves an examination of the processes of laying down of sediment by water or air, and of the rocks formed in this manner. Structural geology deals with the attitudes of the rocks of the crust and with the forces by which they are deformed. Geomorphology is concerned with the shape of the earth's surface, and with the development of topographic forms.

The study of fossils, a very large and important division of geology, is called paleontology; that part dealing exclusively with the plant life of the past is frequently distinguished as paleobotany.

Applications and uses of geology. Geology is an intensely practical science. The United States Geological Survey has been engaged for many years in the construction of a topographic map of the entire country, which will show elevations of the land, the shapes of topographic features, bodies of water, and such works of man as railroads, mines, roads, and even buildings. Up to the present time, about 52 per cent of the country has been mapped in this manner. Other Survey maps show the nature of the rocks which outcrop at the surface. Government geologists have also been very active in accumulating data on rivers, of incalculable value in the construction of water-supply systems or the development of flood-control or drainage projects.

This growing mass of geological knowledge is drawn upon freely by mining geologists and mining engineers in their efforts to extract valuable metals or nonmetals from the earth. The identification of minerals and rocks, the location of ore deposits, the determination of probable yields, and the working out of the structural details of mines and quarries, all fall within the province of the geologist.

The petroleum geologist has contributed more than is generally realized to the progress of modern civilization and to the comfort and happiness of all civilized peoples. One hesitates to estimate what quantity of "black gold" could be obtained from the earth without expert geological study; certainly the amount would be far less than enough to keep the wheels of industry turning at their present rate, and the cost would very probably lay a heavy restraining hand upon the use of automobiles, airplanes, and other agents of transportation.

But it is from the aesthetic or cultural standpoint that geology makes

Never was there a better time than the present to be able to enjoy natural scenery. In these days of extensive travel, a knowledge of the fundamental facts of geology is indispensable to the fullest enjoyment of one's environment. The traveler who possesses a background of geological information sees not only the sheer beauty of the scenes he visits, but is able to enhance his experiences with missing details from his imagination.



Santa Fe Railroad

its widest appeal. Geology is one of the most immediately usable of all the sciences. It is not necessary to put in years of study in order to acquire sufficient proficiency to apply to some extent what has been learned. After a short time the student should be able better to understand and enjoy his surroundings; after a year's work he should be genuinely familiar with much in his environment, natural scenery taking on for him a magnificence and interest which do not exist for the uninformed person.

The traveler in particular will profit from a knowledge of geology. In these days of airplanes, superhighways and superfuels, new travel luxuries offered by the transportation companies, and the increasing leisure which technological advances are forcing upon us, we cannot afford to take the mountains, deserts, and seashores for granted. To do so means to lose much of the potential pleasure of vacation or business journeys. The appreciation of a scene depends very largely upon the ability to supply missing details from the past out of what is stored in the observer's mind. A scene thus becomes alive and



Union Pacific Railroad Photograph

Every vista of nature holds more than majestic heights, bold angles, or sublime colors; it also reveals a lapse of time unsuspected by the average traveler. The rocks cry out their great age, taking the student of geology back to remote epochs of the earth's past, enlarging his mental horizons as few other experiences can do.

moving, as knowledge of its geological background provides materials for the imagination.

The earth has not always possessed the grand scenery which adorns it today. Such scenery, in fact, is the result of circumstances which exist only on comparatively rare occasions. During most of the earth's history its surface, worn by the ageless grinding of river and wind and glacier, has presented an aspect of monotonous rolling plains. It is only during exceptional periods of adjustment that the continents are lifted up, rocks are slowly wrinkled and crushed into mountains, volcanoes break loose, and mesas, canyons, and caverns appear in the rocks. These grand topographic features should be understood and enjoyed to the fullest, and it is the function of any general course in geology to make this possible.

One other result of the study of geology should be mentioned. Geology vastly expands the student's conception of time. Just as astronomy takes him inconceivable distances into space, geology takes him back in time, forcing him to try to think in terms of unimaginable aeons. For the student of either science the world and the universe can never be the same again; petty personal problems must lose some of their significance, and the frontiers of creation must inevitably expand.

The objective of science, according to some, is the ultimate understanding of the universe; according to others, it is the benefiting of humanity. This science of the earth, certainly, can be credited with contributing abundantly to both of these functions.

THE STUDY OF THE EARTH

Observations, old and new. The earliest studies of the earth which properly belong to the modern era were largely the results of observations by interested amateurs. These observations were inscribed in the notebooks of ministers, lawyers, and other professional men whose curiosity and leisure led them to inquire into and describe certain interesting features of the landscape. Attempts at interpretation of the origin and development of such land forms were the beginnings of the intensive studies which evolved into the science of geology.

The casual observations of a century or more ago have been replaced by detailed field and laboratory studies of the earth's materials



Ward's Natural Science Establishment, Inc.

Searching the earth for metals, oil, water—the job of the geologist is both interesting and intensely useful. Geological research raises our standard of living by supplying an abundance of necessary mineral matter at relatively low costs. It also contributes greatly toward an aesthetic enjoyment of nature.

themselves. Thousands of different kinds of minerals, rocks, and fossils have been collected, described, and classified, and each year many kinds not previously identified are being added to the extensive lists. Some of these specimens have been found in surface exposures of the bedrock. Others have been obtained in the process of sinking mine shafts or drilling wells. The geologist, therefore, is no longer limited in his observations to those rocks which appear at the surface of the earth, but has access to information on materials that lie buried as much as three miles or more below the surface.

It is generally true that in the plains areas of the world few of the rock formations present can be seen at the surface. Deep wells may furnish some information about concealed units, but this is at best fragmentary in character. Fortunately another source of information is available. Nearly all plains are bordered by mountain uplifts. In these mountainous regions the rocks have been folded, uplifted, and then deeply dissected by the action of the weather, running water, ice, and similar agencies. Near the exposed cores of the uplifts may be observed the oldest rocks, which, in the adjacent plains, may lie buried

under thousands of feet of sediment. For example, the steeply inclined rocks that form the eastern flank of the Rocky Mountains are also present along the Colorado-Kansas border, where, however, they are several thousand feet below the surface. Similarly, the granite rocks which form the highest peaks of Colorado, Wyoming, and New Mexico are the uplifted and exposed parts of rock masses which in the western parts of Kansas and Nebraska lie miles below the surface.

In addition to the information obtainable from nearby exposures of folded and dissected rocks, smaller and more local uplifts rising abruptly from the plains area occasionally offer important data. The Black Hills of South Dakota, the Llano uplift of central Texas, and the Arbuckle Mountains of Oklahoma are good examples. The term "geological window" has been applied to such features because they offer the geologist a view of formations elsewhere hidden within the earth. By studying the characteristics of the formations exposed in these isolated areas, and by noting the direction and amount of inclination of their beds, it is possible to predict with a considerable amount of accuracy what formations will be encountered at any specified depth in regions miles away from the uplift. The position of water-bearing sands, possible oil-bearing sands, or other substances occurring in the rocks may thus be determined. Of course, if subsurface information obtained by the drilling of deep wells is also available, determinations of the depths and structures of buried formations can be made with greater accuracy.

This principle applies to the interpretation of concealed or deeply buried rock layers of any region. Even though the surface of a county may consist entirely of cultivated soil or of grassland, the geologist may be able to predict the positions and kinds of rocks underlying the area to depths of a mile or more by studying the character and arrangement of the rocks in an adjoining county.

Of course, there is no point on the earth's surface at which complete geological information is obtainable. Even in mountainous areas where exposures are abundant there are always some formations which are obscured or completely hidden by soil and vegetation. Generally speaking, the older rock formations constitute better subjects for study than younger formations, since the former are usually more resistant to the forces which tend to destroy their solidarity. Nevertheless, there is so much difference in the durability of surface rocks that frequently

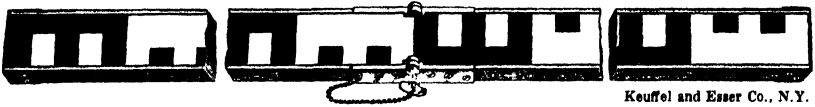
only the harder kinds are readily observable, the softer wearing away and forming valleys, which are usually covered by a mantle of soil, except where cut into by streams.

The younger formations, such as those which underlie most of the coastal plains of the world, are so susceptible to attacks of the weather and are so easily worn away that they seldom present good exposures. In some such instances the dividing line between one formation and another may be detected by differences in the character of the overlying soil, or even by sudden changes in vegetation. A series of springs may emerge along the line of contact of formations of differing permeability, or a number of aligned waterfalls or rapids may indicate a hidden contact between rock masses of differing hardness. In general, any linear arrangement of topographic features controlled by the underlying rock of a region, or of the vegetation of a district, suggests the possibility of change in these underlying formations.

Such signs may fail in those parts of the continents upon which glaciers have left a thick mantle of debris, or where in desert or semi-arid areas winds have deposited dust and sand in considerable thickness. Geologists must then resort to subsurface data obtained from wells or mines and from occasional deep cuts along highways and railroads to supplement the information supplied by nearby areas less completely covered by surficial materials.

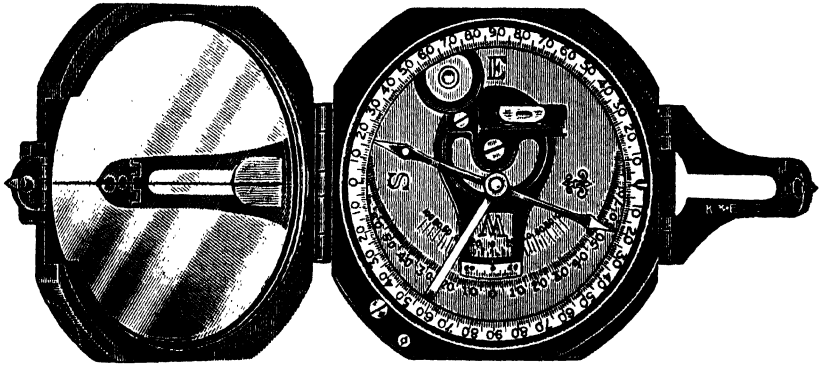
In certain parts of the world, particularly in those areas in which the presence of valuable minerals has been demonstrated, very intensive geological studies have been and are being made. In other sections geological knowledge is very meager. Thousands of square miles of Canada have been subjected to only the most superficial sort of reconnaissance surveys. The geology of Antarctica, study of which may ultimately exert a profound effect upon the interpretation of past conditions in North America, is as yet almost unknown. Most of the countries of the world maintain some sort of state-supported geological bureau, and the number of geologists engaged in commercial work runs into the thousands. And yet many gaps will always remain in our knowledge of the planet on which we live.

Field methods and instruments. Geology, in recent years, has entered upon a more mature phase than that based upon visual observation and inference. The geologist has called to his aid a number of



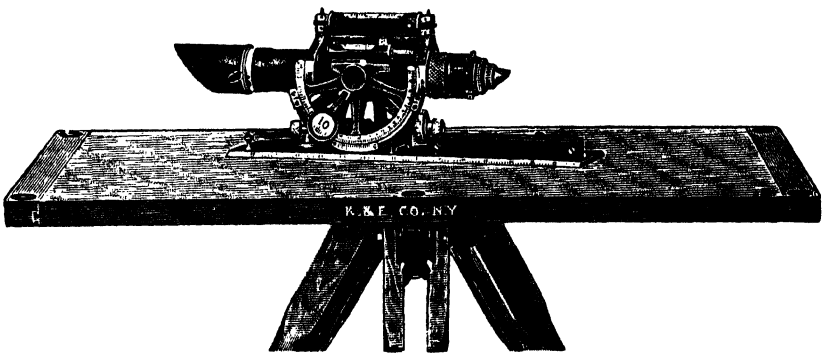
Keuffel and Esser Co., N.Y.

The rod shown above is called a stadia rod and is used in connection with the telescopic alidade to determine horizontal distances. When the two horizontal cross hairs on the telescope of the alidade intercept a vertical distance of 1 foot on the stadia rod, the horizontal distance of the rod from the alidade is 100 feet.



Keuffel and Esser Co., N.Y.

The Brunton compass, or pocket transit, is usually held with the central part resting in a level position in the operator's hand. The sighting bar on the left is centered on the center line of the mirror and the compass direction on the central dial is then read directly. When not in use, both mirror and sighting bar may be folded inward, thereby locking the compass needle.



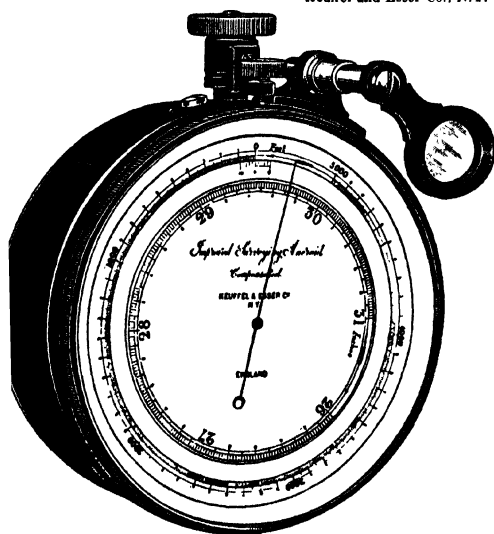
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The telescopic alidade shown here is standing on a plane table, which in turn is mounted on a tripod that permits the table to be leveled but turned in any direction. The large map upon which the observations are recorded is fastened securely to the top of the plane table by means of the corner thumbscrews.

instruments which aid him in a study of rock exposures, and some which probe deeply beneath the surface for rock masses far beyond the reach of direct observation. Data revealed by instrumental methods are plotted on some sort of base map. Aerial photographs are now widely used as base maps for field studies because they not only show exposed rocks and other features of such nature, but also the general topography and major geologic units. Such surveying instruments as the alidade, essentially a short telescope aligned with a graduated straight-edge, by means of which vertical and horizontal angles can be measured and plotted, have been much used in the construction of maps. One type is illustrated on page 13. This method is applicable to the mapping of regions in which rock beds are not too strongly inclined.

If a large area is to be covered in a limited time, detailed mapping may not be feasible. In such a case the field geologist depends mainly upon three or four small instruments which can be carried in his pockets. The first of these is a compass of some sort. The second is a hand level for determining differences in elevation of exposed portions of rock formations. One of the most widely used of all instrumental aids is the *Brunton compass*, in reality a compact pocket transit which serves as both compass and hand level. This is illustrated on page 13. Relative elevations are also sometimes determined by means of the *aneroid barometer*. This instrument, shown on this page, contains an evacuated metal box which changes shape in response to changes in air pressure. Since air pressure changes more or less regu-

Keuffel and Esser Co., N.Y.



The aneroid barometer shown at the left indicates differences in elevation between 0 and 5000 feet. The inner circle is fixed in position and registers air pressure in terms of inches of mercury. The outer circle may be turned and set at any desired point. The reading-glass accessory is to facilitate reading.

larly with altitude, the aneroid can be used to indicate differences in elevation. When in use, it should be checked frequently against a stationary barometer.

In areas of steeply dipping rocks use is often made of the *clinometer*, the function of which is to measure the amount of inclination at any given place. The Brunton compass is equipped with a clinometer; or one can be simply constructed by suspending a small weight from the center of a half-circle divided into degrees.

A hammer, preferably one with one pointed end, is an essential part of the field geologist's equipment. Weathered rocks seldom have the same appearance as freshly broken surfaces. The manner in which some rocks break is in itself a characteristic quality that aids in their identification. The hammer is also needed in removing fossils and other interesting and informative material from the rocks.

Some kind of measuring tape is needed for determining the thickness of beds or larger units. For this purpose tapes of the coiled-spring type are to be preferred because of their accuracy. The thickness of a rock layer is measured across the bed at right angles if possible. If not, a measurement of the exposed portions is made and corrected for the amount of dip of the rock and the slope of the surface.

Recently physics has joined forces with geology in the exploration of the parts of the earth buried beyond reach of the eye. Probably the first of the geophysical methods was the use of the *dip needle*, a magnetized pointer so pivoted as to allow it to move vertically. The device has been employed in locating bodies of magnetic iron ore. Also operating upon the principle of magnetism, but far more sensitive than the dip needle, is the *magnetometer*, which detects minute differences in the magnetic response of rocks which may be deeply buried.

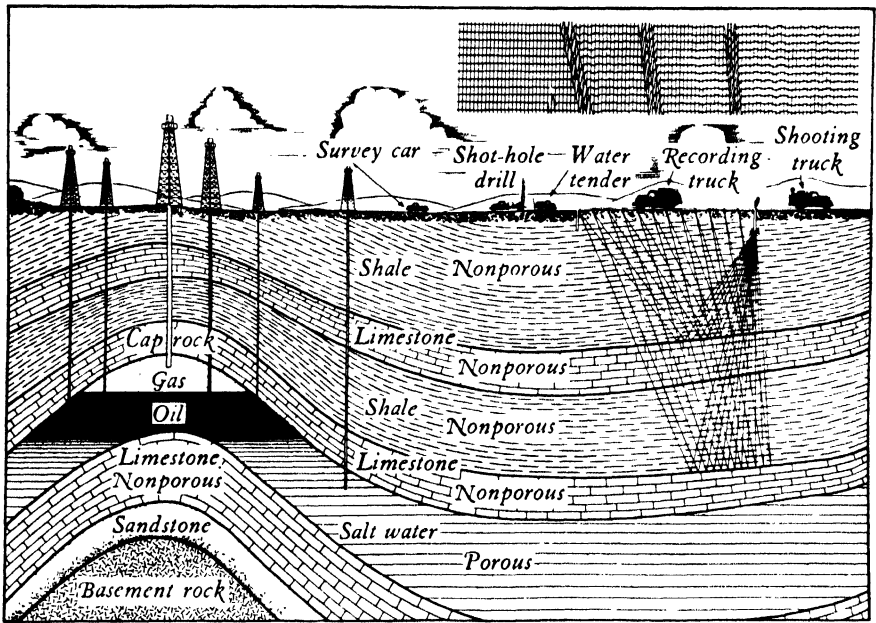
Other geophysical instruments such as the *seismograph* and various types of *gravimeters* have been devised to detect differences in density, elasticity, and conductivity of rock formations. The seismograph, originally used solely for the recording of earthquake tremors, is the most successful and widely used of this class of instruments. In an effort to discover the presence of subsurface rock folds, miniature earthquakes are initiated by means of explosives. By recording the time required for the resulting waves to return to the surface after having been reflected from some hard or well-consolidated formation,

the depth of this formation can be calculated and its position mapped. A diagrammatic representation of the technique employed is shown on page 17.

The basic assumption upon which the results of most geophysical observations are interpreted is that the older, more deeply buried rocks are denser and higher in content of magnetic minerals than are the younger formations which lie above them. The results of geophysical surveys are expressed as anomalies. An anomaly is either a higher or lower value than would normally be expected. A positive anomaly would therefore suggest that the older formations are at the spot in question nearer the surface than elsewhere, and consequently the presence of convexly folded rocks is indicated. The geologist must keep his mind open to the possibility that special conditions have entered the picture to alter results. For example, on the Gulf coast of Texas great plugs of rock salt form large domes in the overlying rocks. Despite the presence of the convex folds, negative anomalies show up in magnetometer surveys of such locations, a result of the quantities of salt. On the other hand, a local concentration of iron oxides near the surface would give a positive anomaly with most geophysical instruments, although totally unrelated to any rock structure.

Despite occasional exceptions, geophysical interpretations are usually accurate and dependable. By means of them hundreds of subsurface folds have been discovered that would probably have never been recognized by other methods.

Some guiding principles. Whatever his method of approach, the geologist must take cognizance of the following facts: (1) *There is no place on the entire earth where a complete record of the rocks is present.* Some areas have been the sites of deposition of sediment for millions of years, whereas other regions have been subjected to the wearing action of natural agencies for equal periods of time. To reconstruct the history of the earth, scattered bits of information from thousands of locations all over the world must be pieced together. The results will be at best only a very incomplete record. If the complete story of the earth is compared to an encyclopedia of thirty volumes, then we can seldom hope to find even one complete volume in a given area. Sometimes a few chapters, perhaps only a paragraph or two, will be the total geological contribution of a region; indeed, we are



Seismograph Service Corporation, Tulsa, Oklahoma

The above diagrammatic chart shows how the seismograph reveals the position of rock strata buried far below the surface.

often reduced to studying scattered bits of information more nearly comparable to a few words or letters. Thus geological knowledge grows from year to year. (2) *Formations at great depths and those concealed by soil and vegetative covering must be interpreted indirectly, as from scattered exposures or from data revealed by geophysical surveys.* An observation of the inclination of a single rock exposure may be the key to the interpretation of a large region. Obviously, the larger the number of such exposed areas, the more accurate the interpretation is likely to be. (3) *The fundamental principle that younger rocks should rest upon older ones is the basis for all correlation attempts, whether such studies are founded on similarities of rocks or of fossils.* (4) *Rocks are so closely related to one another that all types of lateral and vertical gradation may occur.* A formation, for example, which at one point consists almost entirely of the remains of bones and shells of sea organisms may grade laterally as well as vertically into one consisting of indurated mud. Thus such characteristics as color, size of grain, crystallinity, or even chemical composition do not necessarily remain dependable criteria for the identification of a given formation.

II · THE EARTH, ITS MATERIALS AND PROCESSES



From the standpoint of its inhabitants, the earth presents a combination of features so exceptional as to appear to belong in the realm of the miraculous. Its size is just sufficient to hold a good atmosphere, yet not so great as to exert a destructive gravitational effect upon organisms at its surface. Its atmosphere contains ample oxygen to support life upon an active plane, yet not so much as to permit excessive oxidation. The earth's distance from the sun is almost unbelievably consonant with the exacting requirements for life. Protoplasm must have water in liquid form, a condition possible only within precariously narrow temperature limits. These temperature conditions are met only in the minutest fractions of universal space, yet are present on our own planet, thanks to its favorable placement with reference to the sun. Not only is the earth fortunately situated in this respect, but the shape and variability of its orbit are such as to maintain this

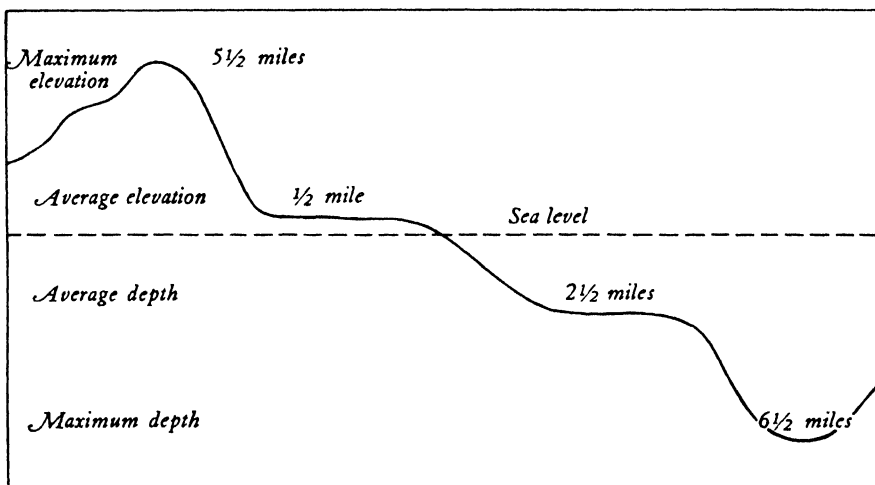


Diagram illustrating average and maximum elevations and depressions of the earth's surface.

delicate temperature balance, the most trivial deviation from which would wipe all life from its surface.

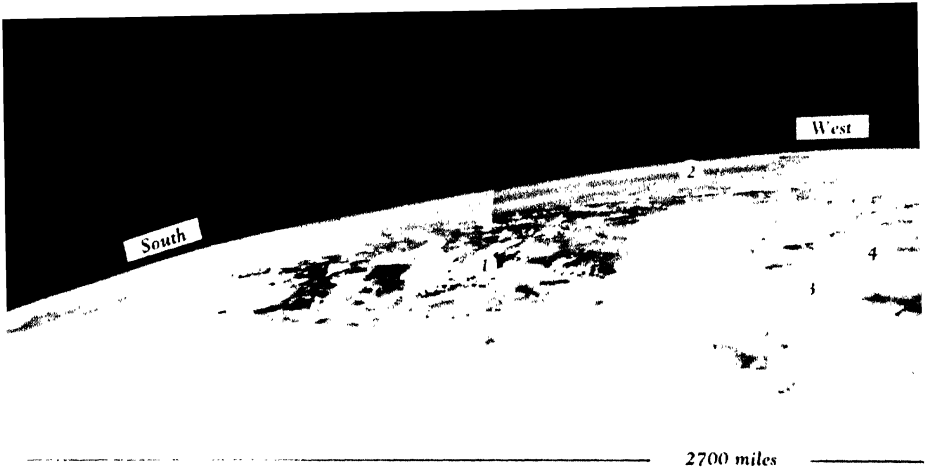
Little wonder that at one time the earth was regarded as the hub of the universe, the center around which all else in the heavens reverently revolved. But from the time of Galileo and Copernicus, the earth has been gradually losing prestige. Grudgingly accepted as a planet, subservient to the sun, it was finally recognized as one of the lesser members of the solar family. The sun, meanwhile, lost its position as a unique body and was found to be but one of the stars, in no important way to be distinguished from the billions of others which constitute the universe. With the discovery that our own vast universe of stars is not the whole sum and substance of creation, but only one of countless numbers of universes scattered through space as far as the telescope can reach, man began to see his home in its true perspective.

MATERIALS OF THE EARTH AND THEIR ORGANIZATION

The face and form of the earth. The earth owes its shape to the interaction of two forces. Any large mass of material will be drawn into spheroidal shape by the power of its own gravitation, and if, like the earth, it is rotating rapidly upon a fixed axis, the centrifugal force developed around its equator will produce a bulge in this region. The earth measures 7900 miles in diameter from one pole to the other; its rotational movement has given it an equatorial diameter about 27 miles greater. Its area is 197,000,000 square miles.

The most outstanding features of the earth's surface are its great continental platforms and its ocean basins. The land surface amounts to about 57,000,000 square miles, or about 29 per cent of the total area. The continents rise to an average height above sea level of a little more than one-half mile, their maximum elevation being five and one-half miles. The average depth of the ocean basins is two and one-half miles, their maximum six and one-half miles, making the maximum relief of the earth more than 12 miles. The diagram on page 18 shows these relationships; no inferences, however, should be drawn from this diagram in regard to horizontal distances.

Viewed in relation to the earth as a whole, these irregularities are utterly insignificant. If the earth were reduced to a globe one quarter of a mile in diameter, the average elevation of the continents would

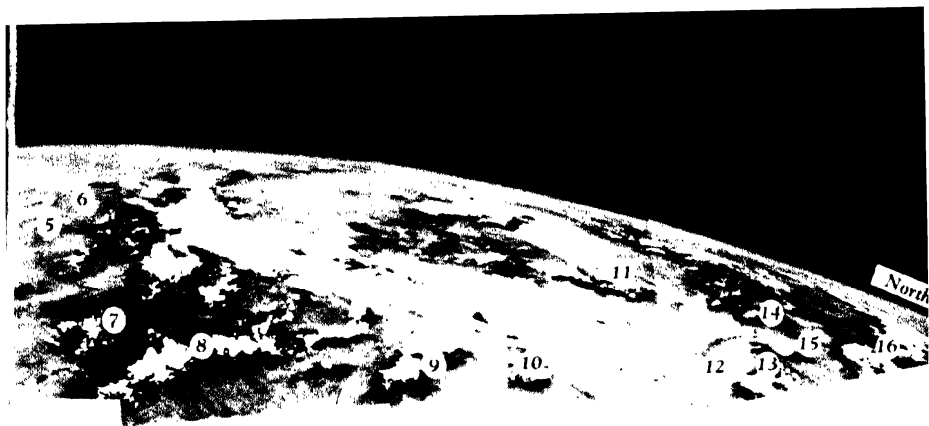


This photograph, taken by a camera carried in a V-2 rocket at an altitude of 60 miles, shows the shape of the earth and the relative magnitudes of its surface irregularities in a very graphic form. The distance indicated is that measured along the curve of the earth, not along the bottom line. The numbers superimposed on the picture identify the following points: (1) Mexico,

amount to one inch, while Mt. Everest would project but ten inches above the sea. If one could observe the earth from an elevation of sixty miles, he would see it not as a sphere dominated by mighty mountains, valleys, and plains, but much as it appears in the composite photograph reproduced on these two pages.

The solid parts of the earth are often referred to as the *lithosphere*, meaning "sphere of rock"; this term, however, is subject to varying definitions. The waters of the earth are thought of as forming a more or less continuous shell known as the *hydrosphere*. This includes the water of lakes and rivers, and that existing beneath the surface of the ground, as well as that of the oceans. The amount of water not contained within the ocean basins is, however, quite small; all the fresh water of the earth would be insufficient to raise sea level more than a few hundred feet. By way of comparison, Goldschmidt estimated that the earth holds some 373 liters of water (including ice) for every square centimeter of surface. Of this amount, 368.45 liters represent oceanic waters, 4.5 liters that existing in the form of glacial ice, and one tenth of a liter the waters of lakes and rivers. Above both rock and water rests the great ocean of gases we call the *atmosphere*.

Near the surface of the earth, air, water, and rock materials are



Official United States Navy Photograph

(2) *Gulf of California*, (3) *Lordsburg, New Mexico*, (4) *Poloncillo Mountains*, (5) *Gila River*, (6) *San Carlos Reservoir*, (7) *Mogollon Mountains*, (8) *Black Range*, (9) *San Mateo Mountains*, (10) *Magdalena Mountains*, (11) *Mount Taylor*, (12) *Albuquerque, New Mexico*, (13) *Sandia Mountains*, (14) *Valle Grande Mountains*, (15) *the Rio Grande*, and (16) *Sangre de Cristo Range*.

intimately intermingled. Particles of the lithosphere in the form of dust are always present in the atmosphere, where they assist in the formation of clouds. The atmosphere also contains quantities of water vapor, which has an important influence on the air's capacity for holding heat, and which under proper conditions will condense into rain or snow. Air is dissolved in the waters of oceans, lakes, and rivers, where it supports animal and plant life, while both atmosphere and hydrosphere penetrate the lithosphere for some distance, making possible the growth of plants upon the land surface.

Rocks and minerals. The earth is made up of more than ninety distinct kinds of matter, or elements. Some of these elemental substances occur free in the rocks, but most of them are found in chemical combination with one another, constituting compounds of definite composition. These naturally-occurring substances, whether elements or compounds, are known as *minerals*, of which a more precise definition will be presented later (p. 369). One of the best-known minerals is quartz, shown on page 22 in the form of the familiar rock crystal. Another common mineral, present in a large number of rocks, is feldspar (p. 22).



Ward's Natural Science Establishment, Inc.

Illinois Geological Survey

(Left) *The ancient Greeks thought that rock crystal, one of the two hundred or more varieties of quartz, was a form of ice which would not melt.* (Right) *Group of feldspar crystals.*

Rocks are *mixtures* of minerals. Their compositions, therefore, are somewhat indefinite, since the amounts and even the kinds of minerals which make them up may vary within certain limits. Rocks grade into one another to some extent in physical and chemical properties. Most of the land surfaces of the earth are covered by a thin layer of loose, unconsolidated rock fragments, including topsoil, subsoil, and loose pieces; these incoherent materials are known as *mantle rock*, and collectively constitute the *mantle*. The mantle varies in thickness from zero up to hundreds of feet. Below the mantle, and in places projecting through it, is the solid *bedrock*, from the disintegration of which the materials of the mantle rock are derived. An exposure of bedrock at the surface is called an *outcrop*.

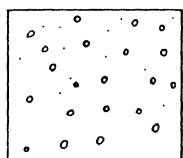
Rocks are classified into three groups. *Igneous* rocks were the first to form on the earth; these are rocks which have solidified directly from a molten condition, without marked subsequent change in structure or composition. Among these granite (see illustration, p. 376), consisting chiefly of the minerals quartz and feldspar, is the best known. Basalt, a denser rock of darker color, is another common igneous rock of wide distribution.

Upon exposure to air and water igneous rocks crumble into particles of various sizes and kinds. By means later to be described these

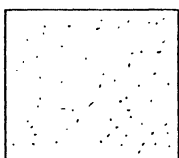
particles are sorted and finally deposited, usually in a succession of layers. These materials may be consolidated by the action of pressure or cementing substances; they then become *sedimentary* rocks, so called because their constituent particles in the great majority of cases settled out of water or air. They are sometimes spoken of loosely as *stratified* rocks, in reference to their deposition in layers, or *strata* (singular, *stratum*). The surfaces separating strata from one another are known as bedding planes. The principal examples of rocks of this class are conglomerate, consisting of cemented gravel or pebbles; sandstone, an assemblage of cemented sand grains, usually fragments of quartz; shale, an indurated mud; and limestone, chiefly the product of the remains of shells and bones of sea animals.

Certain changes may affect both igneous and sedimentary rocks. When such alterations have progressed to a notable degree, the resulting forms are termed *metamorphic* rocks. Among these may be mentioned slate (from shale) and marble (from limestone).

In geological diagrams it is customary to employ certain symbols to designate different kinds of rock, although the use of these symbols is not perfectly uniform. In this book we shall use those shown below:



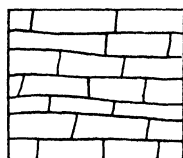
Conglomerate



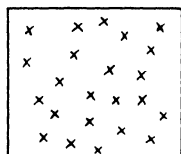
Sand or Sandstone



Shale



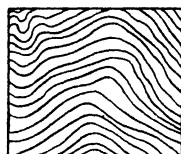
Limestone



or



Igneous rock



Metamorphic rock

Surface occurrence of rocks. Most mantle rock consists of varying mixtures of quartz and feldspar particles, with lesser amounts of other minerals. In many places special circumstances have given the existing mantle rock a distinctive character. Alluvial soils, for example,—those deposited by streams,—are frequently encountered; the vast Russian

plain east of the Ural Mountains is built almost entirely of this type of material. In parts of the Sahara, Kalahari, and Arabian deserts, and elsewhere, great expanses are covered with quartz sand, left behind after the removal of finer particles by the wind. This finer material also forms unique and somewhat extensive deposits of yellowish loam, notably in northern China.

In arid lands the mantle is typically coarse, consisting largely of sand and gravel, while in more humid sections the surface is covered by finer debris. Common in northern North America and Europe, though not unknown in the warmer sections of the globe, are distinctive deposits of mantle rock made by the action of glacial ice; these are typically heterogeneous mixtures of rock fragments of various sizes and compositions.

While of great importance from certain points of view, such as that of agriculture, the superficial layer of rock waste is comparatively very thin, and in places is entirely absent. Of greater significance, for most purposes, is the distribution of the underlying sedimentary, igneous, and metamorphic rocks which make up the bulk of the earth's crust.

Sedimentary rocks, though vastly subordinate in volume to those of igneous origin, probably underlie the mantle over 70 or 80 per cent of the continental surfaces. Most abundant of the sedimentaries is shale, although this rock is often less noticeable in the average landscape than more resistant forms such as sandstone and limestone. Frequently rocks of the latter types are prominent in hills and uplands, while the more widespread shales occupy the floors of low-lying areas where they are usually covered by soil.

With certain exceptions, sedimentary rocks form the plains and lowlands of all continents. One of the greatest expanses of sedimentary rock in the world is the area which includes eastern Scandinavia and

Photograph by H. E. Brown



Horizontally stratified sandstone, revealed by the erosive action of a stream. The other common sedimentary—conglomerate, shale, and limestone—are also often encountered in layers, usually in a stream valley or on the slopes of hillsides or cliffs.

nearly all of Russia. Other very extensive sedimentary tracts lie in Brazil and Argentina, central North America, and intermontane sections of other continents.

In considering rocks from the standpoint of areal distribution, the importance of ice cannot be overlooked; this rock, in fact, covers something like ten per cent of the land surface of the globe at the present time. The bulk of this ice is organized into the immense glaciers which cover the Antarctic Continent and the island of Greenland.

Igneous rocks or metamorphic rocks of igneous origin commonly appear at the surface in regions marked by mountain-forming disturbances. They appear also in plateaus, deep canyons, and in other situations favorable to the removal of the overlying rock.

As a rule granite and similar igneous rocks showing little alteration predominate in the cores of the younger mountains, such as the Alps, Apennines, Atlas, Caucasus, Himalaya, Rocky, and Andes groups. Basalt appears in several extensive and many smaller tracts as a result of relatively recent lava flows. In India basalt covers 200,000 square miles of the Deccan peninsula to an average depth of about 2000 feet, attaining a maximum thickness of more than one mile. The Columbia plateau of the northwestern United States, principally in the states of Washington, Oregon, and Idaho, is an expanse of basalt averaging 500 feet in thickness and covering an area of 225,000 square miles. Iceland, with an area of more than 40,000 square miles, is built chiefly of the same kind of rock, as are many other oceanic islands, notably the Hawaiian group.

In the older mountains, as well as in some of the younger ones, many rocks have been altered into metamorphic forms. Metamorphic rocks constitute the remnants of the oldest mountain system of Europe, to be seen in northern Norway and the Lofoten Islands. Similar rocks appear in ancient uplands of Brazil and Guiana, and in the older sections of the other continents. One of the most notable exposures of metamorphic rock is that of the "Canadian shield," which occupies much of eastern Canada on either side of Hudson Bay; this is the site of very ancient mountains which were long ago worn entirely away.

The earth's interior. Our actual knowledge of the condition and constitution of the earth a few miles beneath our feet is extremely meager. Man has scratched the surface of the globe upon which he

lives to a depth of but slightly more than three miles, although a study of the eroded folds of mountain ranges has extended his insight somewhat further. From these superficial observations, from the behavior of earthquake waves, and from the earth's gravitational relationships three well-established facts have been inferred: the material of the earth's interior is hot, it is rigid, and very heavy.

Deep mines and wells the world over testify that earth temperatures increase with depth. The rate of increase varies from place to place, but amounts, on the average, to something like 1 degree Fahrenheit for every 60 feet of depth. This temperature gradient is doubtless greater near the surface than at greater depths. In any case, there is no reason for believing that any great portion of the rocks is in a molten state, at least in the outer 1800 miles. Melting points of the internal rocks are high because of the pressures they are under. Earthquake waves, including one type which does not travel through liquids, move through the earth just as they would in rigid, elastic rocks. Finally, if any considerable part of the earth were in a liquid condition, enormous tides would be raised in the lithosphere by the attraction of the moon. Actually a tidal deformation amounting to a few inches does occur; but this is no greater than would take place in a globe of steel of similar size.

The mass of the earth is obtained from calculations based upon its observed gravitational effect upon other bodies, either outside the earth itself or in the laboratory. It amounts to 6,000,000,000,000,000,000,000 tons.

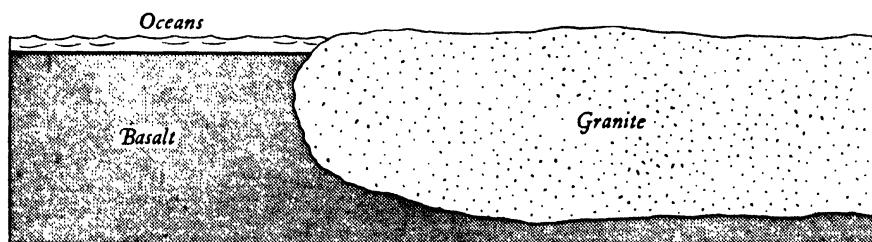
As to the composition of the rocks that make up the earth's inaccessible portions, ultimate knowledge must depend upon the evidence provided by earthquake waves, which have already supplied much valuable data. The rates of propagation of these waves are determined by three properties of the rocks through which they pass: density, rigidity, and compressibility. Since these characteristics can be measured in the laboratory, the rate of wave propagation in any sort of rock can be calculated. In ordinary granites certain of these waves should travel with a velocity of about 3.48 miles per second. This, as a matter of fact, is just the speed at which they do travel through the rocks that make up the continental masses, provided they go no deeper than about twenty-five or thirty miles. At greater depths than this their velocities increase, coinciding with the rates at which such waves

move through rocks of basaltic composition, which are therefore assumed to underlie the continents.

Other evidence supports the view that the continental masses consist principally of granite, floating, as it were, in an ocean of basaltlike rock. Granite appears almost universally wherever overlying sedimentaries have been worn away, and mine shafts and wells deep enough to penetrate these superficial layers also encounter it at no very great depth. The ocean beds, however, appear to be underlain by rocks of basaltic composition; this conclusion is supported both by the testimony of earthquake waves and by the basaltic character of oceanic lava flows.

The ratio between the densities of granite and basalt is comparable to that existing between the densities of ice and water. As a consequence of this fact, the granitic continents lie largely submerged in the heavier rock. North America can be pictured as a film of granite (chiefly), some 3000 miles wide and probably about twenty-five miles in thickness, "floating" like an iceberg in heavy, black basaltic material, with about nine tenths of its mass below the surface of the basalt, one tenth projecting above it. The waters of the oceans occupy basins from which the granite is absent or nearly so; they rise about five sixths of the distance from their beds to the average top of the continental platforms. An approximate idea of these relationships may be obtained from the figures on pages 27 and 28.

Below the crystalline basaltic rock in which the continental masses are suspended lies a region which has been the subject of much dispute. Some very able students of the question hold that the crystalline rock is underlain by a relatively thin layer of essentially the same composition which, however, may be at a temperature too high to permit crystallization. Upon this hypothesis, the rock at this depth is assumed



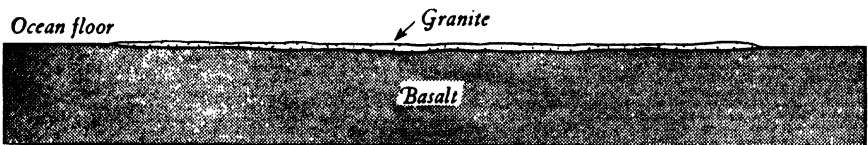
The edge of the "iceberg."

to exist as a hot, glowing glass. Probably the majority of specialists in this field believe that below a depth which may be placed tentatively at forty miles lies some such rock as dunite (consisting almost entirely of the mineral olivine), a theory which the behavior of earthquake waves affecting this section seems to support.

The constitution of deeper levels is attended by even more uncertainty. With increasing depth there occur other layers or shells of exceptionally heavy rocks such as dunite or pyroxenite (consisting chiefly of pyroxene crystals), or mixtures of the two (peridotite). Below these rocks, and down to the earth's metallic core, there may be a mixture of rock and iron, approaching in composition that of some iron-bearing stony meteorites. It is also possible that the core is overlain by a relatively thick layer of metallic oxides and sulfides.

At depths greater than 1800 miles, one kind of earthquake wave undergoes a sudden change in both direction and velocity, while waves of another kind are almost if not quite entirely absorbed by the material which lies below this level. This material, which constitutes the earth's core, has a very high density. As the density of surface rocks averages 2.7 times that of water, while that of the earth as a whole is 5.5 times as great, it is evident that the central portions of the planet must consist of very heavy substances, with a probable density of 10 or more.

As to the composition of these deep-seated materials, we have some strong circumstantial evidence in the composition of the meteorites which occasionally drop to the earth from outer space. These meteorites are considered to be for the most part odds and ends which were left over when the solar system came into existence, separated from the sun by the same cataclysm that gave birth to the planets. If this be so, their composition should approximate that of the earth. We find them to consist of two principal materials, rock and iron, the latter alloyed with small amounts of nickel and other substances. It is a fair



The granite continent floats like an iceberg in an ocean of basalt. East-west cross section of North America.

presumption that during the earth's formative stages its rock and metal portions were separated gravitationally, the latter settling to the center to form the core.

The core's diameter may be set at 4400 miles, giving it a volume of one eighth that of the entire earth. It is presumed to be in a plastic, although not necessarily a liquid, state.

PROCESSES WHICH CHANGE THE EARTH

The rocks at and near the surface of the earth are being modified by a number of agencies. Some of these agencies, such as weathering and metamorphism, function statically, altering the rocks but leaving them in place and having little direct effect upon the aspect of the landscape. Other forces result in a movement of material. Some of the latter act upon the earth from without; these are concerned with the shifting of loose material from place to place. Others have their origin deep within the earth, and these may cause movement of rocks in massive quantities. These agencies may be classified as follows:

1. *Weathering*, which results in or favors the disintegration or decay of rocks near the surface.

2. *Metamorphism*, which is difficult to separate completely from weathering, and which causes marked changes in the rocks affected.

3. *Erosion*, the wearing away of the surface of the lithosphere through the agency of a number of forces. Lowering of the surface of the earth through erosion is termed *degradation*.

4. *Transportation*, or the moving of loose materials from place to place. While gravity is the fundamental cause of transportation, it may act alone or through the medium of special agencies.

5. *Deposition*, or the laying down of transported materials. The term *aggradation* signifies the building up of the earth's surface by this process. *Gradation* includes both degradation and aggradation.

6. *Diastrophism*, which is the movement of parts of the lithosphere through the action of internal forces.

7. *Vulcanism*, which includes the phenomena of volcanoes and other activities involving molten rock.

These processes constitute much of the subject matter of physical geology.

III · WEATHERING



Geology concerns itself largely with two types of changes; first, those resulting from the close intermingling and interacting of the atmosphere, hydrosphere, and lithosphere just described, and second, those originating within the earth. We are for the present concerned with changes of the first class.

The earth's earliest rocks were of course igneous rocks. A granite or basalt buried beyond the reach of the agents of change that exist at the surface might endure indefinitely without alteration. But in the very narrow belt penetrated by air and water many changes, often of a disruptive character, go on constantly. As the surface is worn down, rocks which were originally deeply buried may be exposed. As the pressure they were originally under is reduced, these rocks expand somewhat, and the resulting lessening of cohesion between their grains gives access to gases and liquids. Attacked by various elements of both atmosphere and hydrosphere, the solid bedrock is ultimately reduced to a mass of loose, fragmentary material. The results of this process may be seen in the photograph below.

This process of breaking up bedrock into mantle rock, or of making it softer, more soluble, or of otherwise putting it into a condition favorable to such a change, is known as *weathering*. The term obviously implies alterations due to the action of the weather, but used

United States Geological Survey, photograph by S. R. Cap



Bedrock disintegrating into mantle rock. We see here the effects of frost action and other weathering agencies, which are converting the mountain top into a mass of rock fragments. The accumulating mass, which tends to protect the rock beneath it from further weathering, is called a talus slope.

in the more comprehensive sense indicated above it includes other factors as well, such as certain activities of plants and animals.

Some of the forces of weathering act upon the rock in a mechanical way; breaking up in this manner may be termed *disintegration*. On the other hand, a great deal of weathering is of a chemical nature, causing an alteration of the chemical character of the rock affected, and is therefore spoken of as *decomposition*.

MECHANICAL WEATHERING

Effects of reduced pressure. Rock in quarries has been observed to split suddenly when the removal of overlying or adjacent rock reduced some of the pressure upon it. Unquestionably this same process produces many crevices and seams of weakness in rocks when the overburden is worn away by natural agencies. Such cracks are of primary importance in weathering, as they permit the entrance into the rock of water and atmospheric gases, in this way greatly facilitating other weathering processes.

Freezing. One of the most obvious of the processes of weathering is the disruption of rocks as a result of the freezing of water which has found its way into pores and crevices. When water freezes it expands about one tenth of its volume, and if confined exerts a pressure upon its surroundings amounting to 150 tons per square foot—the equivalent, as has been pointed out, of that of the weight of a column of ice a mile high.

The pores in which freezing first occurs may be small, even microscopic, but they become larger as the process is repeated. Field evidence indicates that the weathering effect of repeated freezing is a factor of considerable importance.

Alternate heating and cooling. Heating causes the expansion of most materials, while cooling results in contraction. If an object consisting of a single material is heated through and through quickly, it expands more or less as a whole; but if a portion only is heated, the resulting expansion of this part produces stress between it and the cooler, unexpanded parts. If the substance is brittle, this stress may result in fragmentation.

As rock is a poor conductor of heat, exposure of a large mass of

rock to the heat of the sun will result in expansion of the outer sections of the mass, while the relatively cool interior parts will remain unaffected. If a drop in temperature should then occur, contraction would occur in the portions of the rock near the surface, but not in the interior.

Much fracturing and scaling off of rocks has been attributed to strains set up by alternate heating and cooling. While presumably a factor in weathering, the importance of this process has probably been overrated, as experimental studies fail to confirm the expected disruptive effect of changes in temperature. Temperature variations several times as great as those to which rock is normally subjected from day to day, repeated for what would be the equivalent of about 250 years, showed not even microscopic changes in the rock under examination. Effects observed in the field may be due in large measure to an internal increase in volume resulting from chemical combination with water, to be described in the following section. Support for this view is found in some of the experiments just cited, in which the introduction of the element of moisture resulted in a distinct weathering effect in a period equivalent to $2\frac{1}{2}$ years.

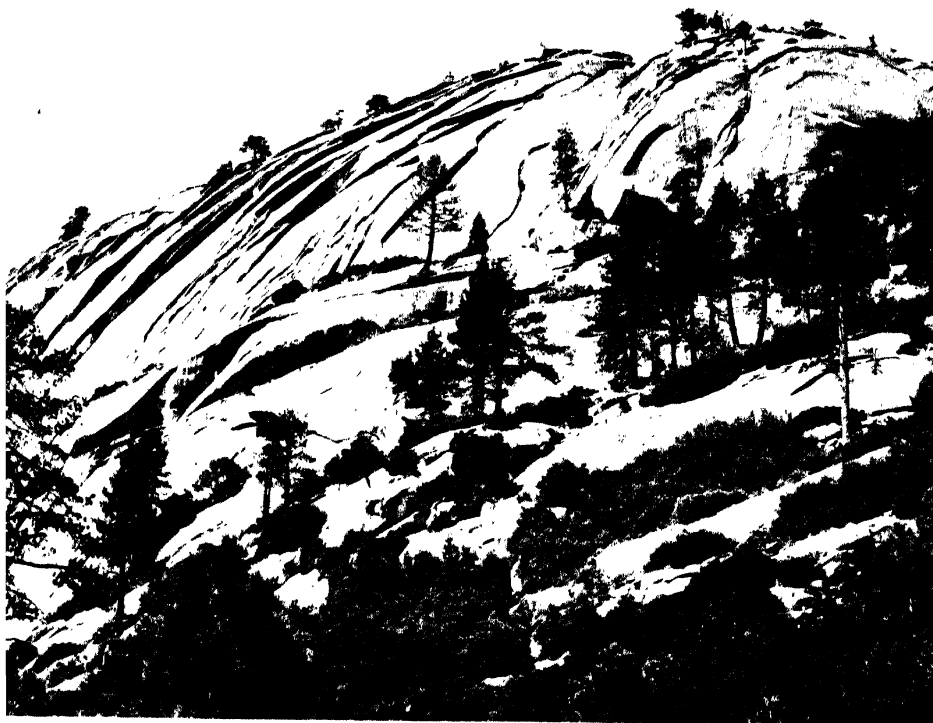
Internal expansion. Certain chemical changes, particularly the incorporation of water into the composition of minerals, result in a marked increase in volume. The weathering of granite through this means, for example, is accompanied by a volume increase of nearly 90 per cent. Although such changes are chemical in themselves, they may produce direct results of a mechanical nature.

Rock which is exposed to the air will dry out for some distance inward from the surface, but will retain water in pores in its deeper parts. Such chemical reactions as have been mentioned may then occur *within*, causing an internal increase in pressure which may well disrupt the surficial portions of the rock. A rock similar to granite, consisting of crystals of different kinds, is under these circumstances

United States Geological Survey, photograph by Kirk Bryan



A boulder showing the effects of exfoliation. The scaling-off process, the result chiefly of frost and internal expansion, attacks protruding corners and edges, gradually reducing the rock to a spheroidal shape.



National Park Service

Exfoliation on a grand scale; disintegration of the Sierras.

most likely to crumble, while one of homogeneous structure may scale off in sheets.

The scaling off of rock around its surface is termed *exfoliation*. Some exfoliating rocks exhibit a shell-like or onionlike construction. The process affects not only small masses, but is to be seen on a grand scale in the Adirondack Mountains, in the Sierras, in Stone Mountain, Georgia, and elsewhere. In these cases great spalls from one or two to more than ten feet in thickness separate from the underlying rock. Such scaling is very unlikely to be wholly the result either of strains set up from without or of pressure generated within; perhaps the relief of pressure brought about by the wearing away of the overlying load is as satisfactory an explanation as any now available. See illustrations on pages 32 and 33.

Organic agents, mechanical effects. The expansive force exerted by a growing root is much greater than is generally realized. In the aggregate, the disruptive work of the roots of plants is of such mag-

nitude as to constitute an important factor in the weathering process. Some plants send roots downward for many feet, not only tending to split the rocks which they enter, but upon the death of the plants leaving numerous openings to which water from above has ready access.

Plants also effect the transfer of large quantities of soluble materials, which are absorbed by the roots and elevated to the surface.

Among the burrowing animals responsible for significant amounts of weathering, the most notable are earthworms, ants, and termites. Earthworms, which are widely distributed in both temperate and tropical latitudes, obtain nourishment from the soil, which they devour as they move through it. At night they emerge upon the surface, where the ingested earth is often cast. Darwin estimated that from seven to eighteen tons of earth per average acre are brought to the surface annually by this means. Worms also drag into their burrows bits of leaves or other organic matter, part of which is eaten, part left to decay.

Ants and termites, especially in the tropics, carry on a truly vast amount of subterranean excavation. Their burrows in some instances are known to be several hundred yards in length, while nests above ground may be built to a height of twenty feet (see page 35); some of lesser height are reported to cover several acres. Ants, like earthworms, may carry leafy material into their burrows.

The effects of man's activities upon the rapidity of rock weathering cannot be overlooked. By plowing the soil and through such activities as mining, quarrying, and excavating basements and foundations he exposes fresh earth to the action of the elements. In fertilizing and irrigating he also contributes to a more rapid destruction of rock, though in these cases it is through chemical rather than through mechanical agencies.

Conditions affecting the mechanical weathering of rock. We should expect that weathering resulting from alternate heating and cooling would proceed most rapidly in regions of thin atmosphere and excessive aridity, since it is such conditions that permit wide temperature fluctuations. Desert temperatures not infrequently show diurnal variations of more than 100° F. This should set up a considerable stress between the surface and underlying portions of exposed rocks. On

the tops of mountains and on high slopes turned toward the sun we should also look for rapid disintegration from this cause. Actually, in neither case is evidence of extensive weathering due to temperature variation very convincing, suggesting, in harmony with the laboratory evidence already referred to, that this type of weathering is in all probability of only minor importance. To the extent that it is a factor, however, its effectiveness will be measured chiefly by the dryness and thinness of the atmosphere.

The conditions favoring effective weathering by ice of course include high latitudes, high altitudes, and a supply of moisture. The process is more rapid in regions of temperatures that fluctuate around the freezing point than in those of continuous cold. Mountain tops

United States Department of Agriculture

An example of modification of topography by organic agents: mound built by termites, Australia. This structure consists partly of soil, partly of masticated vegetation. The weathering effects of termites, as of most organic agents, are to be considered as partly physical and partly chemical in nature. Natives of some sections are reported to hollow out the interiors of termite mounds, using the resulting cavities as living quarters.



often fulfill this condition, and they also as a rule are subjected to heavier rainfall or snowfall than are adjoining lowlands. Many mountains, like the one pictured below, are littered with rock debris which has apparently resulted largely from the action of ice.

Steep slopes are especially favorable to mechanical weathering, since they allow the weathered material to slide away from the site of disintegration, thereby exposing the underlying rock to continued attack.

Sedimentary rocks, because of the large amount of pore space existing between their grains, as well as their relative weakness, are especially subject to disruption through the agency of ice formation. They are, however, very resistant to the effects of temperature changes, as their structure permits expansion and contraction of the individual grains without the development of undue pressure or stress within the mass. A homogeneous composition also makes for resistance in this regard, since expansion or contraction of all components in similar degree would have less disruptive effect than would the more variable changes in volume affecting minerals in a rock of heterogeneous character.

CHEMICAL WEATHERING

Solution. Any process or reaction that dissolves or alters the composition of the rocks of the crust in such a way as to weaken them is to be regarded as a part of the general process of chemical weathering. The most important changes of this kind are those involving *solution*, *hydration*, *oxidation*, and *carbonation*. No substance, probably, is to be regarded as entirely insoluble. When one material dissolves in another, its molecules separate and disperse themselves among those of the other substance (the solvent). Some substances dissolve most

Photograph by H. E. Brown



Mountain tops, because of frequent precipitation and rapidly fluctuating temperatures, are favorable locations for the disruptive work of ice. In this picture we see boulders of weathering accumulating from the breaking up of the solid granite bedrock.

readily in acids; others, such as the common mineral quartz, require solvents of alkaline reaction—that is, those containing bases such as calcium, sodium, potassium, or magnesium. In general, high temperatures and pressures increase solubility. One important exception to this last statement should be noted: gases are much more soluble in cold than in warm liquids.

The solvent power of water for most mineral constituents of the rocks is considerably increased by the presence of the acid-reacting carbon dioxide, which is supplied by the air and by decaying organic matter in the soil. Calcium carbonate, for example, is hardly affected by chemically pure water; in the presence of carbon dioxide, however, it is converted into calcium bicarbonate, which is some twenty-five times as soluble as the ordinary carbonate.

The most important result of the solvent action of ground water on sedimentary rocks is the dissolving of the cements which hold their grains together. In the weathering of igneous rocks, carbonates of potassium and other bases are removed in solution, while silica is leached away during the decomposition of various silicates.

Hydration. The process of chemical combination with water is known as *hydration*. The large increase in bulk that ordinarily results from this reaction has already been noted, as has the disintegrating effect that often follows. Hydration produces a direct weathering effect, in that the products of the process are less dense and as a rule less cohesive than the original materials. Thus the firm feldspar minerals are hydrated to soft clays, and iron minerals to the yellow-brown form of iron "rust." Other silicates are similarly affected.

When hydration occurs in rocks that are so deeply buried that they cannot expand in response to the accession of water, they may, instead of losing density and crumbling away, appear to become harder and more compact than they were at first. When brought to the surface, however, such rocks usually disintegrate rapidly, proving that even in cases of rocks under great pressure hydration is a weathering process.

Oxidation. The surface of almost any rock will exhibit a somewhat different appearance from that presented by a freshly broken exposure. The aspect of the older surface usually is darker, duller, or it may have a rusty look. This difference is generally due to the oxidation and

hydration of iron minerals where they come in contact with air and moisture.

Iron occurs abundantly in igneous rocks in the form of ferro-magnesian silicates such as hornblende, olivine, and black mica, and as magnetite, Fe_3O_4 , and, in less important degree, as pyrite, FeS_2 . Iron in these forms may be oxidized to ferric iron oxide (hematite, Fe_2O_3), which has a red color; or it may, through the process of hydration, be converted into the familiar yellow or brown rust, consisting of the minerals goëthite and limonite.

Pyrite, though never very abundant, is an important mineral from the weathering standpoint. The oxidation of this and of other metallic sulfides produces sulfuric acid, which has a very corrosive action upon many minerals.

Carbonation. The chief role of carbon dioxide in weathering is to increase solubility. Its effect upon the solvent power of natural waters has already been noted. It also combines with many different minerals to form compounds (carbonates) which are in most instances very readily soluble. Thus relatively insoluble iron compounds may be converted into iron carbonate (siderite), which goes into solution easily. Silicates, for the most part extremely resistant to solvent action, may also be changed into carbonates and removed in solution.

Organic agents, chemical effects. The respiration of plants and animals releases carbon dioxide, as does also the decay of organic matter. Other acids and some alkaline substances are liberated from organic material, both living and dead. Even some bacteria have their part to play in the destruction of the rocks of the earth; they are instrumental in effecting the decay of organic matter, and bring about a number of other chemical changes, such as the conversion of ammonia into nitric acid.

Among the first plants to take up residence upon newly exposed rock surfaces are lichens, which owe their ability to exist upon bare earth to the fact that they are not single plants, but a combination of two types, an alga, which manufactures food, and a fungus, which is able to hold water. From pole to pole, on mountain and desert, these tiny plant partnerships establish themselves where nothing else will grow. They promote weathering by keeping the rock upon which

they live damp, by exuding carbon dioxide and other substances which attack the underlying mineral matter directly, and through the effects of the decay of their tissues upon the rock.

Conditions affecting chemical weathering. Chemical changes are facilitated by high temperatures and by the presence of water. High temperatures involve high molecular and submolecular velocities, with consequent frequency of collisions between reacting particles. Water acts in a number of ways in promoting chemical activity. Substances commonly react much more vigorously when in solution than when dry, because solution encourages the breaking up of molecules into atoms or atom groups (ions), and permits free movement and closer, more frequent contacts. Water may also act as a catalytic agent, encouraging reactions in which it does not itself participate; the oxidation of iron in the presence of moisture is an example of this principle. Finally, water itself, as we have seen, often takes the role of one of the reacting substances.

From these fundamental facts, we should expect to find chemical weathering proceeding most vigorously in those parts of the world having warm and humid climates. That such a correlation does exist is very evident. The thickness of the mantle of weathered material in the United States, for example, varies in close conformity with rainfall and temperature, being greatest in the well-watered parts of the southern states and in the Pacific Northwest, and least in the arid sections of the West and Southwest. In the rainy tropics weathering has spread its corroding touch so deeply that the hardest rocks may be weak and crumbly at depths of hundreds of feet. Weathering in the warm, humid regions is further promoted by the growth of lush vegetation, which not only holds water in the surface rocks, but in decaying furnishes carbon dioxide and organic acids to continue the work of decomposition.

Igneous rocks are generally more susceptible to chemical weathering than are those of sedimentary origin. The sedimentaries, in fact, are the already-weathered and reconsolidated products of igneous decay; they have reached a higher degree of adjustment to their environment than have other rocks, and there is usually little in the way of weathering that can affect them except disintegration into smaller particles. Limestone is the only abundant sedimentary rock which



Pikes Peak Information Bureau



United States Forest Service

"Balanced rocks" such as these often result from the cooperation of undercutting and weathering. They tend to assume rounded contours as weathering continues.

yields readily to solution, although gypsum and rock salt might also be mentioned in this connection.

Quartz is not only abundant as a mineral, but is one of the most resistant to all forms of weathering. Consequently, the weathering of igneous rocks of the acidic type is likely to be slower and less complete than of those of basic composition.

SUMMARY OF THE WEATHERING PROCESS

Of the two kinds of weathering, the chemical type is much the more important. It is much the more extensive in scope, as a rule proceeds more rapidly than mechanical disintegration, and generally does a more complete job. Mechanically weathered debris is usually coarse, containing only reduced fragments of the original rock. Materials resulting from chemical weathering are often in a finely pul-

verized condition, and may differ widely in composition from the rock from which they were derived.

The processes of solution, hydration, oxidation, and carbonation have been described separately, but it is to be understood that weathering is ordinarily a complex process in which many different agents co-operate. We may summarize the weathering process as it affects granite somewhat as follows:

Mechanical weathering, chiefly in the form of the action of ice, makes many crevices in the rock. Water, containing dissolved oxygen from the air and carbon dioxide from decaying vegetation, enters these openings. The water partially dissolves some of the more soluble constituents of the rock, while the carbon dioxide combines with iron, calcium, magnesium, and a number of other bases, forming carbonates. The iron carbonate is oxidized and hydrated to limonite and göthite.

Feldspars undergo hydration, becoming clay (kaolin). Potassium, calcium, and other soluble carbonates are washed away, as are quantities of silica, released from broken-down silicates. Quartz grains are unchanged, remaining to form sand.

Thus the end products of the weathering of granite are clay, sand, probably some flakes of resistant mica, and such quantities of soluble salts as have not been leached away by surface or percolating waters.

The region of weathering. Weathering is essentially a shallow phenomenon. Theoretically, it can occur at any depth to which water can penetrate. But the chemical power of ground water generally decreases with depth. This is partly because the movement of water is sluggish at considerable depths, while its content of dissolved matter is there so great that little more can be taken up; and partly because of the progressive loss of certain of the more potent gases which were carried into the ground with it or acquired in the upper layers of soil. Analyses of the oxygen contained in ground water reveal a steady decrease downward; this is probably also the case, though perhaps to a lesser degree, with carbon dioxide. Mechanical weathering is even more strictly limited to the region at or very near the surface.

The fact that the chemical activity of water is increased by heat and pressure tends in some degree to offset the limiting factors mentioned above. Nevertheless, the belt in which weathering occurs on a significant scale is relatively quite thin and close to the surface; it can

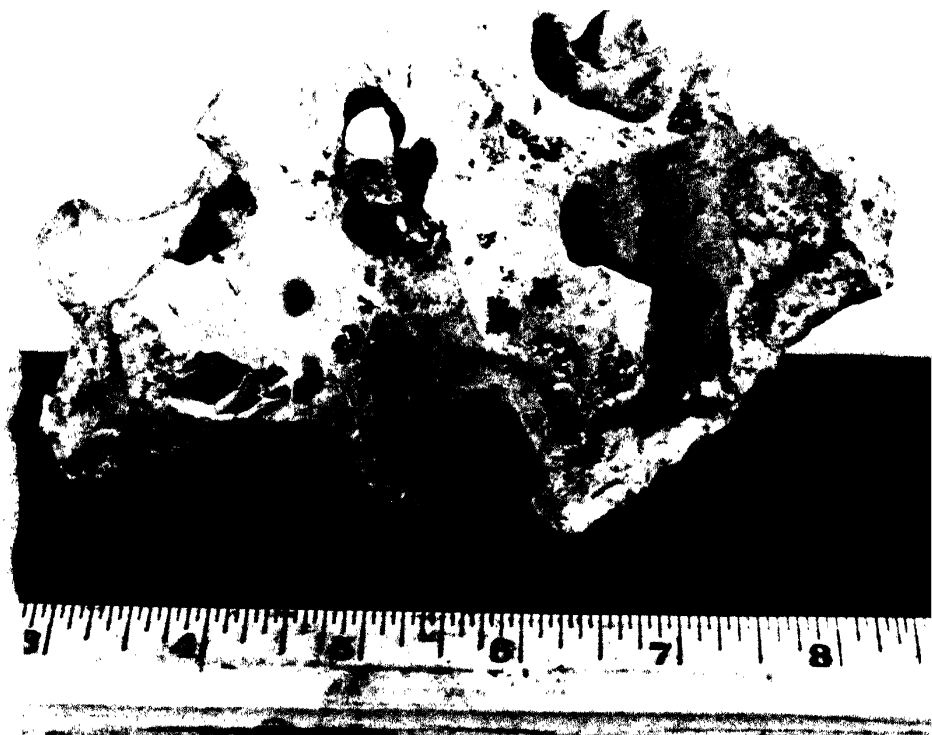
be considered to coincide with the region above the water table, although some weathering does take place for a slight distance below this level.

Products of weathering. In the change of bedrock into mantle rock, the latter may come to lie in place upon the rock from which it has been derived. It is then referred to as *residual mantle* (or residual soil). Mantle rock of this kind shows a gradual increase in coarseness and firmness with depth, merging imperceptibly into the solid, unweathered rock beneath it. Its composition will show relationship to the underlying rock, although certain differences, sometimes important ones, will usually be apparent. Soluble materials will have been removed, wholly or in part; oxygen, water, and often carbon dioxide will have been added.

In other cases, the weathered rock has been carried away from its point of formation, and deposited in some other place; it is then termed *transported mantle*. In such instances a distinct demarcation surface exists between the mantle and the rock upon which it rests. The bedrock may appear quite firm and unaltered, while the material above it is in an advanced state of disintegration. There may indeed be no resemblance whatever between the two, either as to composition or physical condition.

Weathered debris which has fallen from hills or cliffs to form a slope of rock waste is termed *talus*. Coarse material of this kind may stand up at a high angle; finer debris usually spreads out. Talus may accumulate to a depth of a thousand feet or more. The falling of weathered material in this manner exposes the upper parts of the structure on which it originated to further weathering action, but serves to protect the lower portions. Thus the formation of talus slopes contributes to the reduction of irregularities in the topography.

One often observes, especially in regions of fairly moist climate, spherical or oval rocks of the same kind as the bedrock upon which they rest, but often unassociated with soil or other fine products commonly accompanying the weathering of rock. These *boulders of weathering* have resulted from the attacks of various agents, probably predominantly internal hydration in the majority of cases, upon blocks of rock which may have separated from the parent mass through the formation of cracks, or joints. These originally angular blocks weather

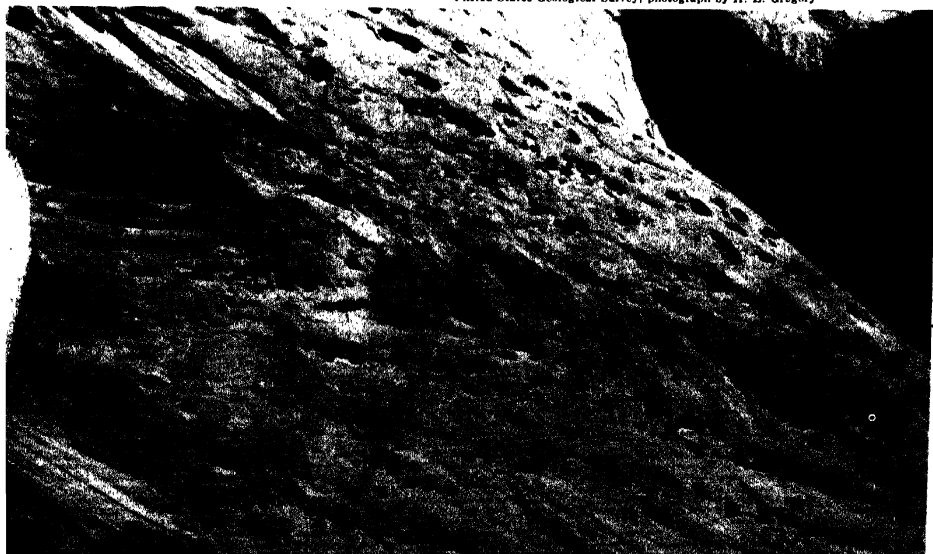


Photograph by Hal Owens

Details of differential weathering in limestone.

The results of differing resistance.

United States Geological Survey, photograph by H. E. Gregory



most rapidly in regions of projecting points or corners, since such prominences are exposed on three or more sides; edges expose two sides to the action of weathering, and flat surfaces only one. Hence the blocks tend to assume a more and more spherical form, because of which the term *spheroidal weathering* is sometimes applied to the process of their formation. The boulders typically exhibit rough surfaces, which usually make them easily recognizable. They become especially conspicuous when the finer weathered particles have been removed by wind, water, or gravity. A typical boulder of weathering, exhibiting most of these characteristics, is shown on page 32.

Differential weathering. If some portions of rock which is undergoing weathering are softer, less compact, more soluble, or for any other reason less resistant than are other parts, these weaker sections will very probably be etched away, leaving the stronger parts standing out in relief. In this way, rocks may be conspicuously pitted, fretted, or grooved, and may be carved into unusual or grotesque shapes, as

Photograph by Robert P. Sharp



Boulder perched on a pedestal about eight feet high, east of the Big Horn Mountains, Wyoming. Structures of this sort are believed to have been produced largely by differential weathering, rather than by erosion by wind-driven sand, as was formerly thought. It will be noted that the pedestal in this case is of a more heterogeneous composition than the boulder, which fact undoubtedly accounts at least in part for the more extensive weathering suffered by the former.

may be seen in the photographs reproduced on page 43. This *differential weathering* is often a contributing factor in the formation of pedestal or "mushroom" rocks, "balanced" rocks, and other such rock remnants. Structures of several different types developed chiefly in this way are pictured on pages 40, 44, and 159.

All solution cavities, of course, are not the result of differing resistance. A horizontal layer of limestone or marble may be pitted with many such depressions which have resulted from the repeated standing of water in slight hollows. Even such striking features as parallel grooves in rock of this kind may be the result of the uniting of numbers of such solution cavities, brought about by a slight inclination of the bed. The illustration on page 47 shows an example of a cliff weathering back along a bedding plane, which is a rather common process. In this case weathering and erosion are effected by water moving along the surface of contact between the two layers of rock.

THE FORMATION OF SOILS

The most important result of the weathering process is the formation of soil. Soil can be defined as that part of the mantle which is in a condition to support plant life. Plant growth requires the presence of at least fifteen different elements, which in most localities are present in the rocks in abundant quantities; in raw rock, however, they are for the most part unavailable to plants. The silicates must be broken down, and nitrates, phosphates, carbonates, and sulfates provided in their place. In this process the weathering effects of living organisms assume a position of prime importance.

As the rock begins to crumble under the attacks of the weather and ground water, and as lichens leave their remains to encourage further decay, bacteria begin the performance of functions highly vital in the process of soil formation. Some hasten the decay of organic matter, certain others capture atmospheric nitrogen and bind it in the soil in a form available to plant life.

The constituents of the primitive soil become finer and finer as weathering progresses. For a time the soil retains characteristics inherited from the parent rock; at this stage it is classified as an *immature* soil. More vegetation is incorporated into the upper portions, and the decay of this material takes oxygen from some of the iron

compounds present, thus reducing them to forms of darker color, while at the same time carbonaceous matter accumulates. For these reasons the topsoil is likely to become dark, perhaps black, although its color depends largely upon climatic conditions. The decaying organic matter loses its identity, becoming *humus*. The carbon dioxide and organic acids released by decaying vegetation dissolve lime, iron compounds, and other minerals from the topsoil, carrying them downward into the partially weathered rock below, where some of them may be deposited. The material in this lower section, usually of a lighter color than that above, constitutes the *subsoil*, which grades imperceptibly into the relatively unaltered rock beneath it.

As weathering continues, silt grains are reduced to microscopic size. With the absorption of water, they then become gelatinous, and are said to be in a *colloidal* state. Very fine organic particles also become part of the soil colloids; these colloids have an important influence upon fertility and the agricultural behavior of the soil. Eventually the soil has lost all resemblance to the rock from which it was developed, and it is then said to be *mature*.

The ultimate nature of a soil is determined more by a number of factors attending its development than by the nature of the rock from which it originated. One of the chief factors concerned is rainfall, by which much soluble plant food is leached out of the soil, leaving it in an impoverished condition. The soils of the drier parts of the United States are far more fertile, generally speaking, than are those of the well-watered northwest coastal region or of the East. A map showing the average rainfall in different sections of the United States appears on page 65.

As has been pointed out, the solvent activity of water in the ground is increased by humus in the soil, and is therefore likely to be high in regions of abundant vegetation. Humus, however, is destroyed rapidly by soil bacteria, which thrive under conditions of high temperature. Hence in the tropics and warmer parts of the temperate zones humus is deficient—often practically absent—in low, well-drained areas, existing in quantity only in swamps where lack of air inhibits bacterial activity, and at higher altitudes where low temperatures serve the same purpose.

Red soils generally indicate a deficiency of organic matter; they betray the presence of ferric iron, which cannot be reduced to the less



Photograph by A. Y. Owen

Weathering is often especially rapid along bedding planes. Here we see a heavy stratum of limestone overlying shale. The surface of the shale stops the downward percolation of ground water, which makes its way laterally along the contact.

conspicuous ferrous form or converted into iron carbonate and removed in solution because of the small quantity of decaying organic material in the soil. An extreme example of the effects of low humus content and heavy rainfall is to be seen in the extensive tracts of *laterite* to be found in Brazil, India, Africa, and elsewhere in the tropics and subtropics, where humus is destroyed by bacterial action almost as soon as it is formed. Laterite consists chiefly of varying proportions of iron and aluminum oxides and hydrated oxides which in the absence of carbon dioxide and other acids derived from humus accumulate as the more soluble materials are leached away by abundant ground water. Tropical soils are as a rule poor, and can be utilized for agricultural purposes only through the continued application of fertilizer.

In general it may be said that an annual rainfall of more than twenty-five inches causes excessive leaching. For this reason, next to saving the soil itself, fertilization is the foremost agricultural problem of the East, while shortage of water remains the greatest barrier to crop production in most of the western states. The great wheat-growing belt is balanced precariously between these two limiting factors.

WEATHERING AND TOPOGRAPHY

Much of the interesting scenery of the world has been produced or profoundly influenced by uneven weathering. The first effect of weathering upon mountains or other elevated structures is in most cases to make them more rugged. Peaks and crags emerge as less resistant rocks weather away. But in the course of time even the hardest prominences are erased, and mountains take on a rounded, more flowing outline.

The scenic aspect of any region is determined very largely by its elevation, its climate, the type of rock underlying it, and the attitude of this rock. In a region of folded sedimentary rock, for example, ample rainfall is likely to result in a landscape featured by sandstone hills and shaley valleys. In an arid region, on the other hand, limestone may stand out above other sedimentaries, although this rock commonly succumbs to the effects of solution in localities in which water and vegetation are plentiful.

Since siliceous rocks resist the attacks of weathering more successfully than do the basic types, rocks such as granite and basalt, if in

association, tend respectively to form elevations and depressions. Vertical *dikes* of basaltic rock, instead of protruding as ridges, have been known to weather to deep grooves.

Vertical lines in a landscape, if of general occurrence, point to an arid climate and considerable elevation. The mechanical weathering characteristic of such a climate is slow and its effects are confined almost entirely to the surface of the rock which, being little affected internally, is therefore able to support the steep walls of cliffs and canyons. In more humid regions, chemical weathering prevails; the agents of this type carry on their work scores or even hundreds of feet beneath the surface, softening and weakening the rock to such an extent that steep walls or sharp outlines cannot well be maintained (compare illustrations on pages 350 and 351). In the West, land of aridity and generally high elevation, we find many examples of angular outlines etched on the landscape by the bold artistry of the weather. While such figures are not unknown in the eastern parts of the country, the topography in this section takes a more mellow turn, and is characterized by the smoother, more finished workmanship of abundant water.

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IV · TRANSPORTATION OF WEATHERED MATERIAL AS A RESULT OF GRAVITATION



Irregularities in the surface of the earth are the results of partial and temporary victories of the rocks over gravitation. The ever-present tug of the earth on all parts of its surface tends constantly to pull the more elevated portions to lower levels. This effect is opposed by the strength of the rocks and by friction (the opposition encountered when rough surfaces are rubbed together). Any factor which reduces the cohesiveness of the rock or lessens its friction promotes the leveling action of gravitation.

Weathering, in diminishing the cohesion of rocks, prepares the way for the work of degradation. In some cases rock undergoing weathering may be so placed that this process is all that is needed to cause the falling, slipping, or rolling of broken-off particles into lower positions; in other situations, the help of special agents may be required in moving the material. The present chapter deals with dislocations of surface material chiefly through the action of gravity alone. Subsequent chapters will discuss changes produced by gravity acting through the agency of such forces as wind, running water, or glacial ice.

Slide-rock and talus. In the simplest case, weathering loosens and sets free particles which slide or fall to lower positions. These particles constitute *slide-rock*. Such incoherent materials, produced by weathering on cliffs or hillsides, may accumulate at the base of the elevation as a talus slope, examples of which are shown in the illustrations on pages 52 and 53.

The material of a talus slope tends to differentiate, the finer particles rolling or sliding farther down the slope than the coarser, more angular pieces. Rainwash may also pick up some of the smaller particles from the mass and carry them to lower levels. Except for these effects, the accumulation is unassorted. The larger, more freshly weathered fragments generally lodge near the top of the mass, where



Photograph by Robert P. Sharp

The Gros Ventre landslide just east of Jackson Hole, Wyoming, occurred in 1925, damming Gros Ventre River and forming a lake 3 miles long and 200 feet deep.

they may form slopes standing at angles of 30° to 40° to the horizontal; further weathering reduces them in size, breaks them up, and rounds off their projecting points and edges, so that they ultimately roll or slip farther down the slope. This finer, rounded material is incapable of forming steep slopes; consequently, talus slopes are generally concave in shape, gradually flattening out downward as their constituent particles become finer and finer, until in many cases they merge imperceptibly with the general surface of the land.

This generalized picture is subject to various modifications. Large boulders, for example, may occasionally develop sufficient momentum to carry them far down the talus slope, to lodge on top of much finer fragments. In winter, piles or ridges of coarse material may come to rest near the foot of the slope, transported over the frozen ground by snowslides. Talus accumulations are always modified somewhat by the impact of rain and by water running over their surfaces.



United States Forest Service

Talus accumulating on the slopes of the Devil's Post Pile, San Joaquin Valley, California.

Mass movements. When a considerable amount of material slides to a lower level as a mass, rather than as individual particles, the movement is termed a *slump* if on a small scale, and a *landslide* if great quantities of rock are involved. Slump occurs frequently in the walls of valleys, especially as the result of undercutting by streams or glaciers. Even the smallest of streams may induce slump on a considerable scale, as may be seen in the illustration on page 54. Steep hillsides covered by poorly consolidated rock or by a thick mantle of weathered material sometimes exhibit numerous small hummocks or terraces, the results of many minor slumps at different points.

Landslides occur in response to a number of conditions. The most common cause is the accumulation on a steep slope of a large amount of weathered material, into which seeps much water from rains or from the melting of snows. The water adds to the gravitational stress the material is under by increasing its weight, at the same time acting as a lubricant, reducing the friction which has held the accumulated

rock in place. Because of its more or less heterogeneous composition, the weathered mantle will vary from place to place in its capacity for absorbing water. It will also vary in the amount and kind of mud that is formed. Hence the mantle does not usually slip down the mountain side as a unit, but its different parts move somewhat independently. The resulting topography is likely to show great irregularities, like that pictured on page 57.

It is not always loose, fragmental material that thunders down a mountain slope, uprooting trees, damming streams, overwhelming settlements that lie in its path. Sometimes immense masses of the solid bedrock break loose and crash downward. This occurs, usually, on the sides of valleys which have been deepened rapidly, leaving sheer cliffs, or along steep ocean shores where rocks have been undercut by the waves. Even some of the engineering projects undertaken by man, such as the building of roads or the making of railroad cuts through mountainous areas, may produce steep slopes or cliffs favorable to landslides. Under these conditions, when great masses of rock have been left unsupported on one side, the strength of the rock may not be equal to the demands gravitation makes upon it, and a landslide

Huge deposits of talus, standing at high angles. Alaska.

United States Geological Survey, photograph by F. H. Moffitt





Soil Conservation Service

Slumping is common along many streams.

These small slumps resulted from the activity of rills and brooklets several yards back from the main stream bank.

Soil Conservation Service



results. A landslide is especially likely to occur if rock strata dip toward the valley; in this case, water working its way downward along the top of a shale or clay layer may so lubricate the latter that the overlying rock slides off.

Joints, or cracks in rocks, also frequently serve as planes of weakness which contribute to the probability of landslides. This was true in the case of the disastrous and spectacular landslide which destroyed the town of Frank, Alberta, in 1903. Forty million cubic yards of rock suddenly broke loose from the top and side of nearby Turtle Mountain, and plunged 3000 feet into the valley. The rock mass was broken to bits, but did not stop moving; so great was its momentum that it moved outward from the base of the mountain, crossing the two-mile valley and rising 400 feet on the opposite side. Seventy people were killed in this catastrophe.

When large masses of rock come to be situated in unstable elevated positions, landslides may be touched off by earthquakes. The deadly quake which rocked the Kan-su province of China in 1920, claiming between 100,000 and 200,000 lives, owed its destructiveness chiefly to landslides it produced in the poorly consolidated materials prevalent in that district. Large quantities of weathered rock lying on precipitous slopes, perched boulders, and similar bits of mantle rock in elevated positions are accepted as evidence that earthquakes have long been absent from the region in question.

The Turtle Mountain landslide occupied only about two minutes. Many such earth movements, however, are much slower; on slopes of lesser inclination spasmodic movement in different parts of the mass may continue for years.

Accumulations of debris resulting from slumping or landslides are of course entirely unsorted. This material consists of sharp, angular fragments if the slide involved bedrock; otherwise such effects of weathering as it exhibits will depend upon the nature of the region concerned and the depth of rock removed in the slide. The shape of a deposit of this kind will be determined largely by the topography of the region. An uneven, hummocky surface frequently develops, especially in a region which has undergone numerous small, localized slumps.

An *avalanche* is the sudden descent of a large accumulation of snow. It is a geological agent of some significance, as it usually carries

with it a considerable amount of mantle rock. Repeated avalanches whose courses are confined by the walls of valleys or large joints (see page 58) may effect an important amount of erosion. Both landslides and avalanches have left their unmistakable marks upon many mountains, among them those of the western United States. These appear as bare gashes, standing out vividly on forested slopes.

In less obvious but in the aggregate more important ways the surfaces of the continents are settling to lower and lower levels. Everywhere the rock seeks to flatten out, bedrock and mantle rock alike. At a rate often measurable in centuries rather than in years the solid parts of the earth slowly gravitate toward a common level. This imperceptibly slow downward movement is called *creep*.

The causes of creep are various. If grains of soil, having settled into positions of relative stability, are disturbed from any cause whatever, the rearrangement that results is likely to leave them in lower positions than before. The enlargement of growing roots creates much pressure, which forces the soil particles out of their former positions. When this occurs on a slope a net downward displacement usually results, because of the pull of gravity on the down-slope side. The activities of burrowing animals have the same effect. Holes left by roots after the death of the plants, the burrows of ants and earthworms, the cavities produced by the removal of materials in solution, all make the ground more porous and hence more susceptible to compression from the weight of rock material at higher levels. This compression is effected chiefly by movement down the slope.

When heavier soils dry out, cracks form in them, the openings forming largely through movement of soil toward the down-slope side, as indicated in the diagram on page 59. Upon the next wetting by rain, the soil swells and the cracks may close up; in this case movement is principally on the part of the soil on the higher side of the crack, which also moves down the slope. In some types of soil, heaving, or lifting from below, is a conspicuous result of the formation of frost in the ground. If this occurs on a sloping surface, soil particles are not lifted vertically, but in a direction approximately perpendicular to the surface of the ground. Upon the melting of the ice, however, the particles do not return to their original positions, but tend to settle *vertically* downward, as shown in the accompanying diagram (p. 59). Expansion and contraction of the constituents of soil on a slope result-



United States Forest Service

Avalanche marks on the heavily timbered mountains of the San Juan National Forest, Colorado.

Landslide topography in the San Juan Mountains, Colorado.

United States Geological Survey





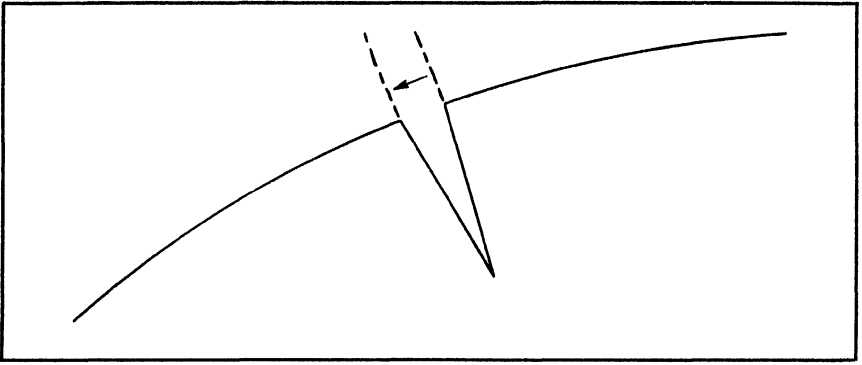
United States Geological Survey, photograph by Jackson

Mount of the Holy Cross, Colorado. The cross is formed by intersecting joints. Avalanches travel downward through the more nearly vertical of the joints, deepening and lengthening it.

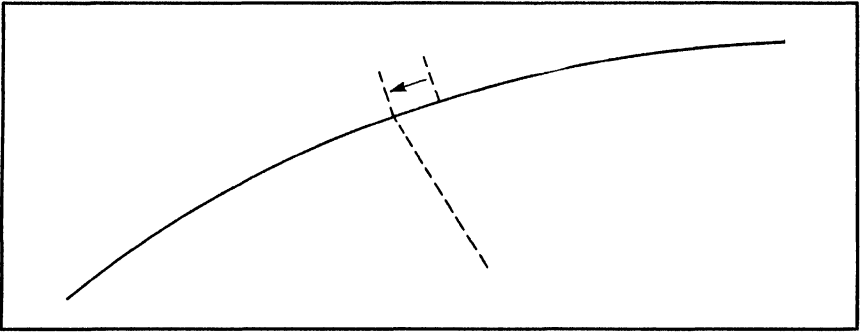
ing from changing temperatures also causes movement, again chiefly toward lower levels.

We may assume that even such influences as the gravitational strains produced by the sun and moon, which may cause tides in solid rock amounting to several inches, disturb rock particles sufficiently to allow their readjustment into generally lowered positions. The falling apart of disintegrating rocks, and any casual disturbances due to miscellaneous causes contribute to this downward migration.

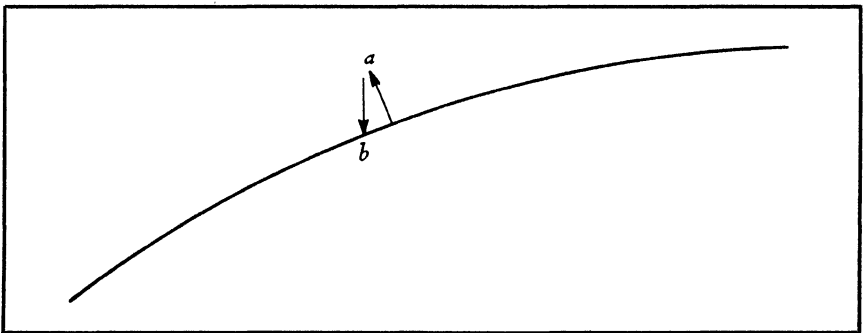
An important factor in the promotion of creep is the entrance of water into the pores of the soil. The water acts as it does in precipitating a landslide, adding to the weight of the weathered material and serving as a lubricant, allowing the grains to slip over one another



As a clayey slope dries out, cracks form chiefly through the movement away from the opening of the down-slope side in the direction indicated by the arrow.



As the crack closes upon absorption of water by the soil, most of the movement occurs in the up-slope side.



Freezing tends to lift soil particles in the direction indicated by arrow a; thawing drops them vertically, as to position b.

readily. Such saturated soil may flow beneath sod, without greatly disturbing the surface, or it may slowly move the overlying vegetation along with it. In the far North and upon high mountains where the ground is perpetually frozen, except for a very short distance below the surface, water plays an especially significant part in the creep of materials near the surface. Upon the thawing during the summer season of this superficial region, the water cannot seep downward into the still hard-frozen ground below; it forms with the soil a thick mud, sometimes a number of feet in thickness, which slowly flows toward lower ground, becoming a confused mixture of sand, silt, and pebbles. This type of creep is known as *solifluction*, or soil flowage.

Occasionally the removal of surface material may expose bedrock, the upper portions of which have been bent over by the creep of unconsolidated rock particles above.

On low slopes the rate of soil creep is generally inappreciable over periods of a number of years. On steeper inclines it may amount to several inches per year. Old fences or retaining walls on hillsides frequently show an accumulation of earth against their up-slope sides. The trunks of trees are sometimes tilted by the downward displacement of the soil about their roots, and they may even develop a curved shape, bending convexly down the slope in their efforts to grow into the normal vertical position.

Perhaps to be classified as intermediate between landslides and creep are *mudflows*. In many of the Western states extensive rivers of mud have moved down mountain sides, sometimes causing much damage when they emerged from mountain valleys upon cultivated land. Mudflows are typical of regions of infrequent rains. Weathered material which has accumulated in large quantity is picked up by the rain water, forming a thick mud. As the mass moves forward it encounters more weathered particles; its forward end becomes a viscous wall, holding back the more fluid portions behind it. When this wall is at last broken through, the out-rushing liquid carries its slimy load forward rapidly, spreading it out into a fan or sheet. An extensive mudflow in Colorado is shown in the photograph on page 61. The magnitude of this flow can be appreciated by noting the trees which have grown up upon it.

Mudflows and solifluction bring about a thorough mixing of the participating ingredients. Little opportunity for sorting exists. The



United States Geological Survey, photograph by Cross

Slumgullion mud flow. Lake San Cristobal, Colorado. Lake San Cristobal was formed by the damming of a stream course by this flow.

force of mudflows issuing from mountain valleys is sometimes so great that boulders several feet in diameter may be carried along and incorporated in the deposited mass.

Rock streams, also known as "rock glaciers," "rock flows," and "rock rivers," are masses of talus material of coarse sizes which are slowly traveling down mountain slopes. Sometimes they move within the confines of valley walls, sometimes in the open. As the rocks high in the mountains disintegrate and fall upon the stream, the added weight of the fresh acquisitions contributes to the movement of the entire mass. The expansion of freezing water between the stones is also an important factor in causing movement. A rock stream flows more readily if a considerable proportion of its mass consists of relatively small pebbles.

Rock streams are to be found in the mountains of Colorado, Oregon, and other states. Although little known, these structures are often



United States Geological Survey, photograph by F. H. Moffitt

A rock stream, pushing its way imperceptibly downward among the mountains of Alaska. Appearing from the distance like a rather typical glacier, this river of stones is an example of one of the ways in which rock, like water, seeks its own level. Its course may take it over cliffs and through basins, thus simulating the course of a stream of water. Rocks breaking off from the mountain slopes above continually join the migrating mass, their weight adding to the pressure which keeps it in motion.

quite spectacular and of unusual interest. Their courses may take them over cliffs, where they form rock "cascades," and they may enter or depart from large expanded deposits which might be termed rock "lakes."

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V · THE WORK OF RUNNING WATER

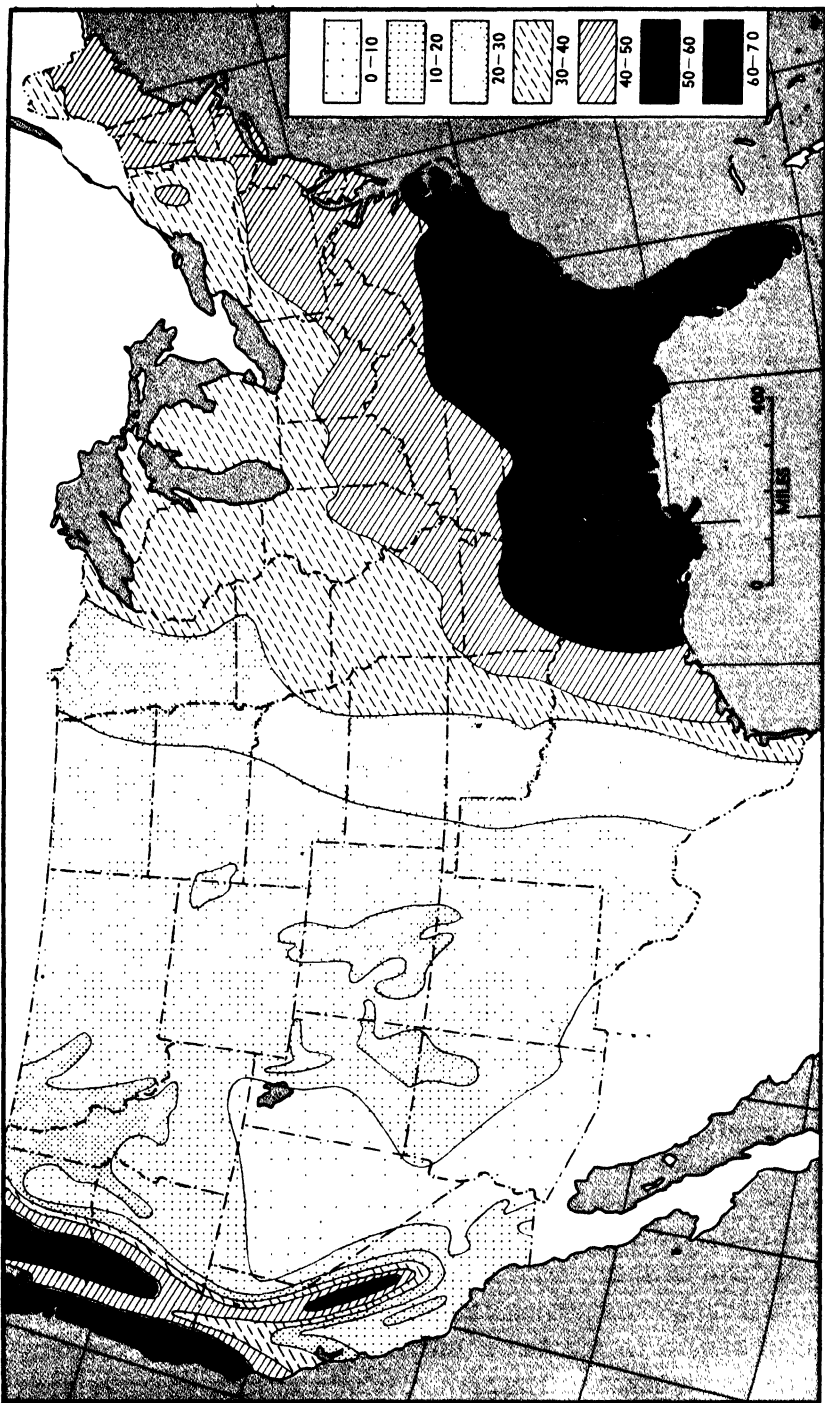


One of the most important of all the processes affecting the earth and its inhabitants is the constant evaporation of water from its surface, followed by precipitation in the form of rain or snow. Century after century this water cycle continues, providing life-giving moisture for terrestrial organisms and supplying energy for the wearing down of continents and for the removal of the resulting debris. Some of the water which falls as rain evaporates immediately into the atmosphere; some sinks into the ground, becoming *ground water*; another portion, the *runoff*, finds its way into the beds of rivers or lakes. A distinction is sometimes made between *surface runoff* and *ground water runoff*; the former term is applied to rainfall which has entered stream channels or lake basins directly, the latter to water which has emerged from the ground through springs.

The proportion of rain water which becomes runoff varies with conditions from zero to nearly 100 per cent. On the whole, about one third of all the water that falls upon the land surfaces of the earth eventually enters bodies of surface water. Maximum runoff is to be expected in regions having relatively impervious rocks, steep slopes, little vegetation, concentrated rainfall, and a climate that is sufficiently humid and cool to prevent excessive evaporation.

The volume of running water on the continents, in relation to that of the entire hydrosphere, is quite insignificant. As a geological agent, however, this water exerts an influence out of all proportion to its abundance. Aided by weathering, it is by far the most effective of all the agents of erosion and transportation.

Runoff waters always contain quantities of dissolved solids, the nature of which varies with the types of rock with which they have been in contact. In general, the most abundant constituent of rivers in fertile and well-watered regions is calcium carbonate. In rivers which drain more arid regions, such as many of those of the western and southwestern United States, sulfates and chlorides may predominate over the carbonates. The average salinity of river waters is about



Rainfall map of the United States. Symbols on the right indicate the average annual rainfall in inches.

100 parts of dissolved solids per million parts of water, or about 1/350 that of ocean water.

A large proportion of the total runoff is carried by a very few of the world's largest rivers, the dimensions of which are given in the following table:

River	Length (miles)	Drainage Basin (square miles)
Amazon	4000	2,722,000
Congo	3000	1,425,000
Mississippi-Missouri	4200	1,240,000
Nile	3473	1,107,000
Rio de la Plata	2300	1,198,000
Yangtze	3000	650,000

RAIN AND RAINWASH

Recent studies have revealed rain as a geologic agent of greater importance than has been hitherto supposed, especially when viewed from the economic standpoint. An average of 15 million tons of water

Overgrazing of hilly range land leads to splash erosion. Here sparse grass has offered so little protection against raindrops that all organic matter, including seeds, has been splashed downhill, inviting wind erosion and leaving the soil too poor to support new growth.

United States Forest Service



per second drops upon the earth; more than a billion tons may fall during a single shower. The force with which the individual raindrops strike the surface depends upon their weight and the rate at which they are moving. The speed of a falling raindrop is quite variable, the maximum being in the neighborhood of 25 feet per second; those shown in the illustration on page 67 are approaching this speed.

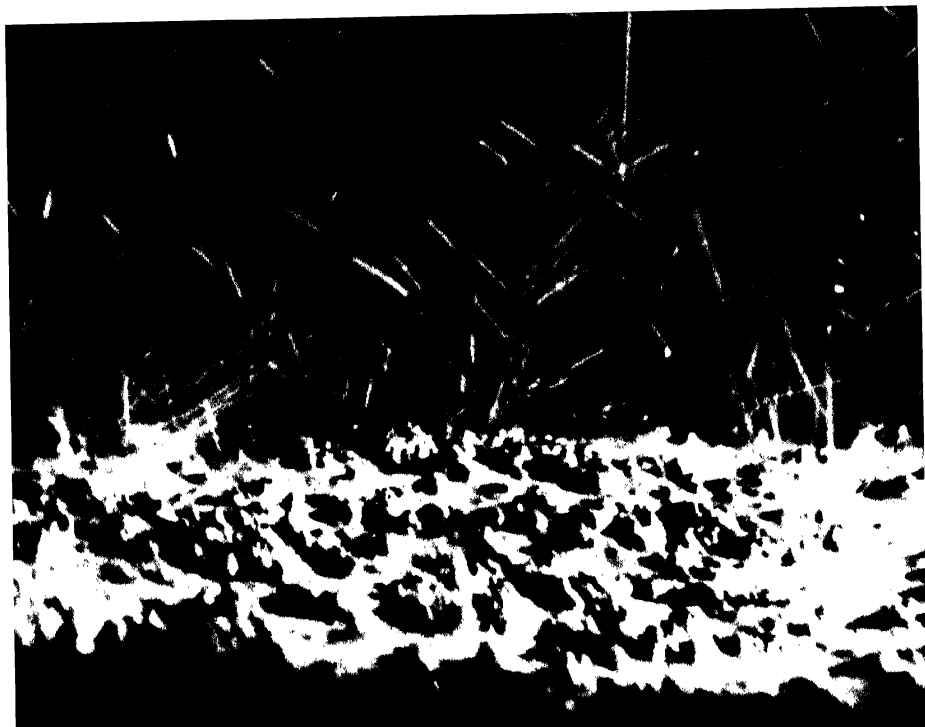
The effect of falling rain upon well-consolidated materials or upon those well-covered by vegetation is, on the whole, slight. The average annual rainfall the world over is about 33 inches; this means that the weight of water falling on an average square inch of surface is only a little more than one pound per year. Also the lightness and softness of the individual raindrops render their impact ineffectual in many situations.

It is in soft, loose, or extensively weathered material that the erosional effect of falling rain assumes important proportions. In sloping cultivated fields or overgrazed ranges raindrops beat into the soil with results seldom realized. Soil particles may be displaced several inches by a falling drop (see illustration referred to above). A hard rain is capable of dislodging and moving as much as 100 tons of earth particles per acre by this means alone.

The dislodging of soil particles results in an immediate net shift of a sheet of soil to lower levels. In addition, the particles are likely to be swept downward by the sheet of water flowing over the surface. Some of the serious economic results of this process are pictured in the illustrations on pages 68 and 69; equally serious effects are those suggested by the diagram on page 70, which shows what is happening farther down the slopes. Here the richest of the topsoil removed from the higher parts of the area is covered, during successive rains, by topsoil of less and less fertility, and the whole accumulation finally buried by subsoil, when the topsoil from the hills becomes exhausted. It is believed that soil loss from this cause amounts to a great deal more than that due to the washing of soil into stream channels.

Even on land that is fairly flat, sheet erosion may exact a severe toll. The effects of displacement of particles by the impact of raindrops on flat land, however, is not considered serious.

Rain is directly responsible for certain other changes in the soil. By causing the adherence of clayey particles at and near the surface, it often produces a thin layer of hard, impervious material overlying



Soil Conservation Service

First stage of rain erosion. Raindrops are striking the earth at a rate of 14 miles per hour, while the splash water contains as much as 40 per cent mud. A hard one-inch rain can move as much as 170 tons per acre.

the rest of the soil. This impervious crust increases surface runoff, subjecting the slope to gully erosion, causes dryness, which is injurious to the organic contents of the soil, and interferes with proper aeration.

The illustration on page 68 shows the effects of rain erosion after this hard surface layer has been broken through over most of the area. Dislocation by falling drops has lowered the surface except where remnants of the hard crust have protected the underlying soil from attack from above, producing miniature columns. Rain may co-operate with weathering and gully erosion in the formation of columns, often on a larger scale; in cases such as those shown on page 71, resistant strata may serve to protect weaker strata below them, or protection may be afforded by pebbles or boulders scattered through the formations. Note also the illustration on page 71, which shows a mushroom-shaped feature probably due principally to rain erosion.

Rain often serves to give a coarser texture to soils exposed on slopes. In the illustration shown on page 65 we see a slope which because of

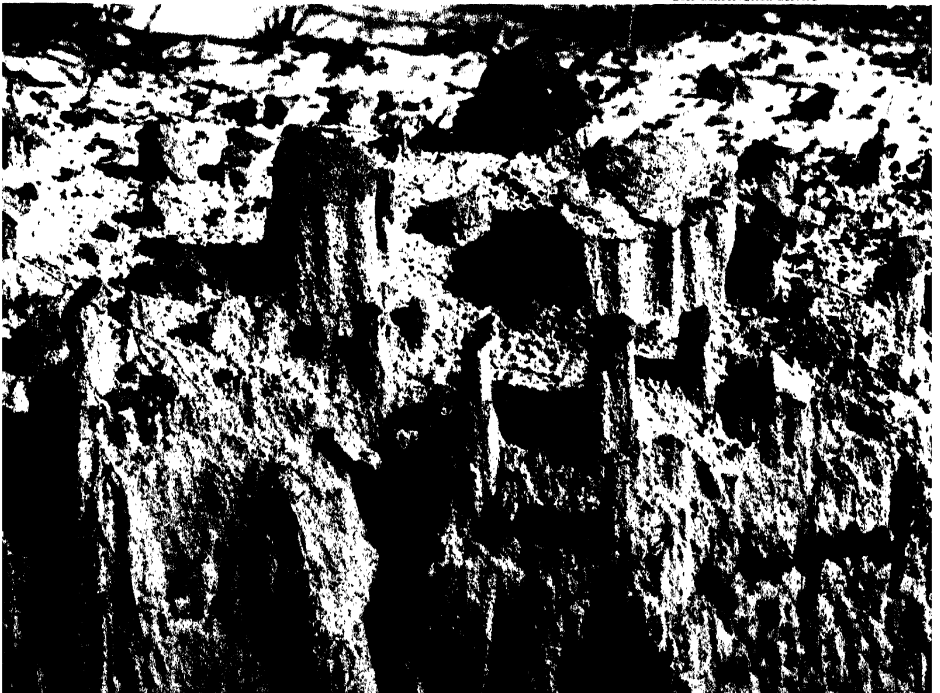
overgrazing has been severely attacked by rain. Soil particles were broken up, and organic matter and the finer inorganic constituents were gradually moved down the slope. Soils so affected can in many cases be made productive again only by employing drastic and highly expensive methods, for they may have become so poor through the removal of their more valuable mineral and organic constituents that they will no longer support vegetation, and are thus exposed to still further erosional losses.

STREAMS AND THEIR VALLEYS

Origin and development of valleys. Before a flowing sheet of water has traveled very far, it begins to break up into rivulets occupying small gullies. The original cause of these gullies may be found in differential erosion, resulting from irregularity of slopes or from differences in hardness. Once started, however, they tend to enlarge themselves, and their growth is often alarmingly rapid. Rain water concentrates itself in them, developing greater eroding power here

Later stage of rain erosion. Driving raindrops broke through the hardened crust which formed over the surface during dry weather, and then actively wore away the softer soil beneath. The shape of each column of soil was determined by that of the patch of crust which remained intact.

Soil Conservation Service





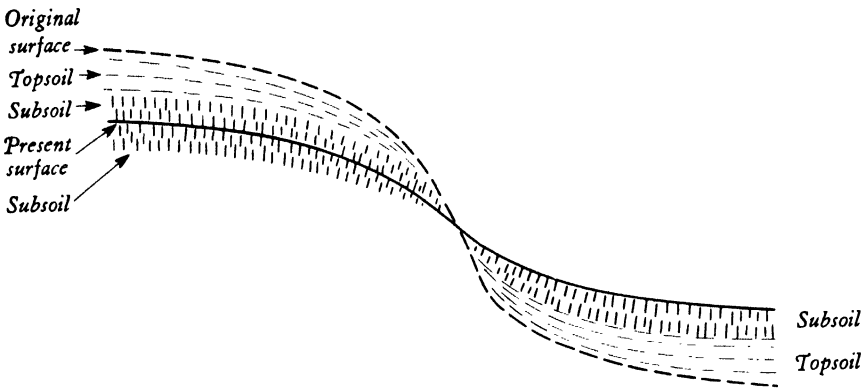
Soil Conservation Service, photograph by T. A. Pasto

Results of sheet erosion. Topsoil has been completely removed over a period of several years.

than on equal areas of the general slope; hence the bottoms of gullies are lowered more rapidly than the surfaces of the divides which separate them. The upper end of a gully, and also its side walls, have steeper slopes than the general ground surface; rainwash consequently runs with greater speed down these slopes, causing the gully to extend itself both headward and sideward. A very early stage of this process is shown in the illustration on page 72.

Along the course of a gully or ravine started in this way, tributary gullies begin to take form. Beginning often as the result of unequal hardness of rock material along the sides of the main gully, or of inequalities of slope, these tributaries grow and branch out, working themselves headward away from the parent valley, and rebranching repeatedly. They normally form with their main valley an acute angle which faces upstream, although this usual type of junction is often modified by the attitude of the underlying rock. Such a system of gullies ordinarily leads to a river or a body of standing water.

In the course of their development, many of the smaller gullies are swallowed up by adjacent larger ones. A larger quantity of water, a



An important cause of topsoil loss. Displacement by the impact of raindrops and by rainwash transfers soil from the upper portions of the slope to the lower, where it is buried by later deposits, and eventually by infertile subsoil.

softer bed, or a swifter flow may give one stream greater eroding power than that of its neighbor. In such a case, the divide between them is shifted in the direction of the weaker stream. The tributaries of the stronger stream, having a greater fall, will grow more rapidly than those of the weaker, and at length one of them may penetrate the latter's channel, draining off its headwaters into that of the more rapidly eroding stream. This process is called *stream piracy*, and the stream which has lost its headwaters is said to have been *beheaded*. The illustrations on page 74 show stages in this process.

An instructive case of potential piracy is revealed on the Edmond, Oklahoma, map (p. 440). Here the Canadian River stands about 1120 feet above sea level, and is in danger of being beheaded by one of its tributaries, which stands at this point some 120 feet lower. At the point indicated by the arrow the smaller but more rapidly eroding stream has extended a tributary to within one-quarter mile of the flood plains of the Canadian, while the divide stands only a little more than 40 feet above its water. The tributary, although intermittent, has a fall or gradient in excess of 60 feet per mile, and should have little difficulty in cutting through the remaining barrier.

In this case the cause of the difference in the rapidity of erosion is to be found in the heavy load which the larger stream is forced to



Geological Survey of Canada United States Geological Survey, photograph by Kirk Bryan

(Left) Pinnacles developed by rain and rainwash through the protective action of boulders scattered through glacial moraine. Hoodoo Valley, Banff, Alberta. (Right) This mushroom-shaped structure is formed of a large block of horizontally bedded conglomerate resting upon a pedestal of less resistant shale. Disintegration of the shale was probably due more to the action of rain than to that of wind.

carry. The excessive amount of debris encumbering the waters of the Canadian long ago put an end to its down-cutting activities, and resulted in the building of a flood plain approximately a mile in width.

Streams flowing in courses determined solely by the slope and shape of the surface are known as *consequent streams*. These occur commonly on low coastal plain slopes. In the course of their development most streams are forced to adjust themselves to the bedrock underlying the surface, and, as a result of this adjustment, may alter their original courses, establishing routes which follow the softer of the underlying rocks, avoiding the harder rock wherever possible and crossing it by the shortest possible paths. Streams which have thus adjusted themselves to the bedrock of a region are classified as *subsequent streams*.

The shape of a valley in cross section depends largely upon the relative efficiency of the processes of weathering and erosion. If weathering is ineffective compared to the process of down-cutting,

the valley will develop steep banks, which may even be vertical or nearly so. If weathering is predominant, as is often especially the case during the later stages of valley development, width will be great in relation to depth.

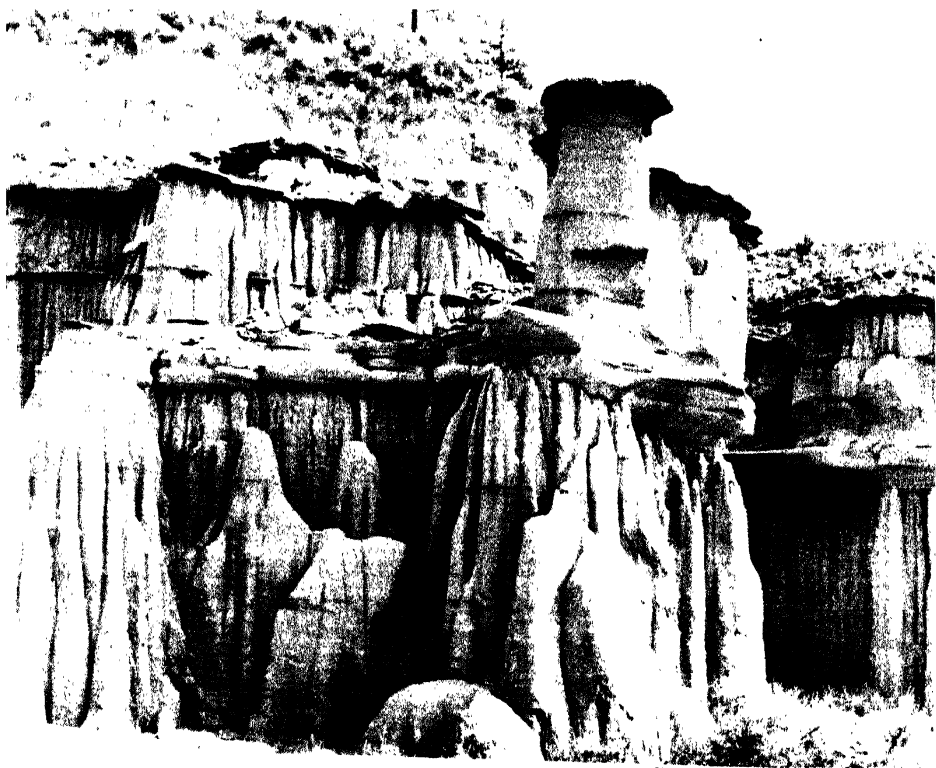
A *river system* consists of a main valley and all its tributaries and subtributaries. A *river valley* is the valley which has been excavated, either wholly or in part, by the stream which occupies it. The trough in the bottom of the valley in which the water flows is the stream's *channel*. A river's *drainage basin* (or *watershed*) is the entire tract or country drained by the river and its tributaries.

The flow of streams. A stream's gradient is its fall over a stated distance. Only a very slight inclination of its bed is necessary to keep a stream moving. Over much of its course the Amazon River has a fall of but one fifth of an inch per mile, but its great volume of water keeps it flowing steadily. Most streams have much higher gradients, ranging from several inches to several feet per mile.

Initial stage of valley-formation. A few decades ago this mountain, near Butte, Montana, was heavily wooded and almost free from gullies. The trees were killed by fumes from the copper smelters, and many gullies immediately established themselves. At the present stage these small valleys are straight and but little branched.

United States Forest Service





United States Forest Service

*Erosion is the master sculptor; it does its best work in rock of varying hardness.
Scene in Custer National Forest, Montana.*

The flow of water in a stream is never a simple mass movement. Many minor upward and lateral currents occur, the results of irregularities of the bottom and banks. Friction with the channel retards flow, causing the water near the banks of a stream to move more slowly than that near the center, and that at the bottom to move more slowly than that near the surface.

The velocity of a stream is determined by several factors: the gradient, the volume of water, the shape and course of the channel, and the amount of material carried along by the water. Steep gradient, large volume, straight narrow channel, and little load promote swiftness of flow.

The erosional aging of streams. The normal history of a stream conforms to a rather definite pattern, which may be compared to that of the life of an individual. Successive stages have therefore been designated as *youth*, *maturity*, and *old age*.



Stream piracy. In the lefthand picture, the rapidly eroding stream on the left is growing headward and will soon intersect the stream on the right. In the righthand picture, this result has been accomplished, and all water is now carried off through the channel of the invading stream.

During its youthful stages, the stream is the slave of its environment. It has not yet mastered the terrane it traverses, not yet established itself as the dominant factor of the topography. Its course is marked by many irregularities. Rapids, waterfalls, and projecting spurs interrupt its flow. Gradients are high; banks are steep-sided and are broken by but a few poorly developed tributaries.

Youth is a time of abundant energy—more energy, in fact, than is needed to do the work at hand. It is a time of rapid erosion, and the struggle of the river with its surroundings is reflected in the boldest, most inspiring, and most artistic effects.

At maturity a large measure of adjustment has been effected. There has been a smoothing out of the stream's gradient. Waterfalls and rapids have by this time been ground away. The stage of rapid down-cutting has passed; hence the stream's valley is more rounded in shape, with less precipitous sides. The land has been lowered, reducing the stream's gradient; coincidentally with this lowering, tributary valleys have been branching out, bringing in ever larger loads of sediment for the main stream to carry. Because of these two conditions, the main stream is eventually brought to "grade."

A *graded stream* may be defined as one all of the energy of which is consumed in carrying its load, with none left over for further down-

cutting. Although this condition may be more theoretical than real, it may be taken to mark the peak point of maturity, following which the stream's erosional activities are directed horizontally, cutting away its banks rather than degrading its bottom, and are accompanied by the deposition of surplus sediment across its valley.

Old age is a time of decrepitude for the stream. It is a time of depleted energy, resulting from very low gradients, and of a load so heavy that little of it can be carried, the surplus being spread out in broad valley flats. The stream becomes sluggish, and wanders from side to side in wide bends. Floods are of common occurrence.

"Old age" normally begins at the mouth of a stream, and creeps slowly toward its headwaters. Thus it is usual to find a stream exhibiting signs of youth near its source, maturity farther down, and old age near its lower extremity.

From what has been said it may be seen that the age of a stream is not a matter of years, but of erosion. Such factors as elevation

The Grand Canyon of the Colorado, "most sublime of all earthly spectacles."

Union Pacific Railroad Photograph



above the sea, the kind of rock, the type of weathering, and the supply of water determine whether youth shall last a million years or more, or whether maturity and old age come on apace. The Colorado River with its turbulent water and its mile-deep canyon exhibits all the characteristics of youth after the lapse of ages, while a rivulet in soft earth near sea level may be robbed of all signs of youth and precipitated into old age by the same shower that gave it birth.

STREAM EROSION

Nature of the Erosional Process

The term *erosion* (Latin *e*, "off," and *rodere*, "to gnaw") is often used rather vaguely, and in somewhat different senses by different writers. As employed here it signifies all processes whereby rock, either solid or fragmental, is removed from its position as a part of the mass to which it originally belonged. Erosion is obviously related to weathering on the one hand and to transportation on the other. Weathering is usually a very important adjunct to the actual loosening and removal of rock particles, and is treated by some authors as a part of the erosional process. It is clear too that only a theoretical distinction can be made between erosion and the transportation of materials from place to place, since of this process erosion forms the initial step. Although these processes may be studied separately as a matter of convenience, the close relationship existing between them should be kept in mind.

Weathering is accomplished through the agency of processes which leave the rock upon which they act in place. Erosion, on the other hand, involves the removal of the rock. The agents of erosion are rain, running water, percolating water, waves, currents, wind, and ice.

Activating these agents of erosion is the force of gravitation, which provides the energy for the movement of air and water in all their forms. There are times when gravitation acts directly in causing the removal of weathered material without the intervention of any of these special agents, as has been explained in Chapter IV.

Methods of stream erosion. Under some circumstances material is removed from the stream bed as a result of the force of the water

itself. Generally speaking, the effects of direct hydraulic action are slight unless the rock is weak or the force of the current is strong. If, however, the rock over which the stream flows consists of grains cemented by soluble substances, it is readily broken up and removed. The presence of cracks in the rocks of the bed or the arrangement of these rocks in thin layers also aids the stream in working loose and picking up the material. The removal of rock by such means may be called *quarrying*; this form of erosion produces most of the pebbles and boulders which are rolled along the bottom of the stream, and which by their impacts continue the work of erosion.

Most of the erosive work of a stream is the result of the grinding or scouring action of sand and pebbles on its bottom and sides. Even a very swift stream will have little wearing power on its bed if some sediment is not present. For example, all the force of the Niagara cataract is insufficient to sweep away the delicate plant life which flourishes upon the face of the falls. If the Niagara River carried as much grit as the average river, such growths could never maintain a foothold.

Streams also erode their beds by means of solvent action. Limestone, gypsum, and other readily soluble materials are removed in this way, sometimes on a considerable scale. Cementing materials or other constituents of the rocks are dissolved, opening the way to effective hydraulic or abrasive action. In most cases, however, only a small fraction of the dissolved matter in river water has been taken from the river's bed; most by far has been brought in by ground water which has found its way into the stream channel.

Effects on transported materials. The various agents of erosion leave their distinctive marks upon the materials they carry, impressing them with their own peculiar erosive methods. Running water shows a strong tendency to obliterate or reduce projecting points and edges on particles small enough to be moved, provided they are not so small that they are transported chiefly in suspension. Even a journey of as little as one mile down a vigorous stream may be sufficient to produce a definite rounding effect such as is characteristic of river wear (illustrations, pp. 90 and 191). If the rock is homogeneous and without internal structure it becomes more nearly spherical the farther it travels; but if it possesses any sort of "grain," such as might result



Union Pacific Railroad Photograph

The Grand Canyon of the Yellowstone River, and the Lower Yellowstone Falls. Lava intrusions across the river's course are responsible for this V-shaped valley and the falls, which are twice the height of Niagara.

from weakness caused by cleavage planes, it will be more likely to assume a flattened or oval shape. In either case the rounding is clearly recognizable.

River pebbles are smooth, consisting usually of quartz or some other exceptionally resistant material. Feldspars and other softer minerals are quickly ground up into mud. These characteristics serve to distinguish water-carved rocks from boulders of weathering, which commonly have rough exteriors, and may consist of almost any kind of rock.

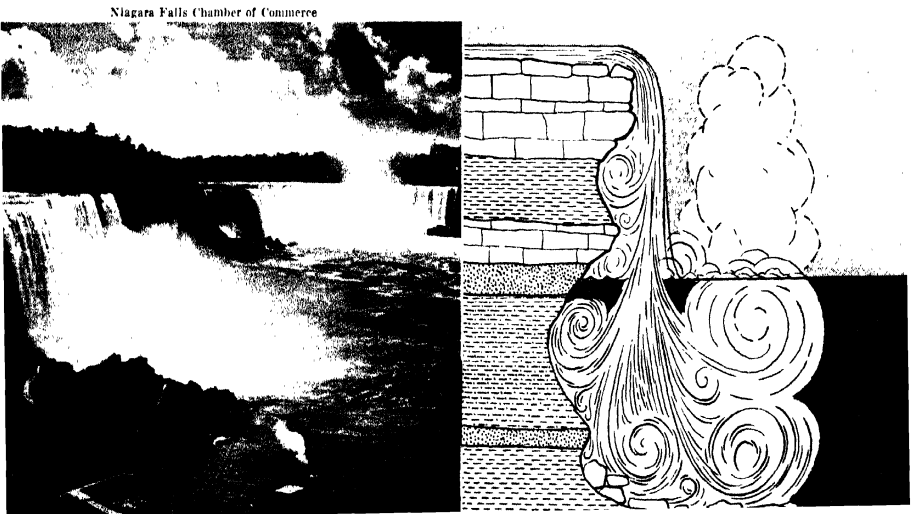
Topographic Effects of Stream Erosion

Canyons. Some valleys are structural—that is, the result of the attitude of the bedrock which underlies them. The great majority, however, have been produced by the erosive action of running water.

The shape of a river valley is determined by the interaction of the processes of weathering and erosion, as well as by the nature and the attitude of the rock. If erosion proceeds rapidly in comparison with weathering, the valley attains considerable depth in relation to its width, and may become a canyon.

The conditions which cause down-cutting to outstrip weathering—assuming an adequate supply of water in the stream itself—are chiefly *high elevation* and *aridity*. Elevation gives streams high gradients

Niagara Falls, and a diagram showing the conditions responsible for its existence.



with consequent high eroding power, while an arid climate is reflected in weathering of the mechanical type, which, being slow and confined in its effects to rocks at or very near the surface, leaves banks in firm, solid condition and capable of standing at high angles.

In streams with high gradients, downward erosion is so rapid that many irregular spurs are likely to be left projecting into the valleys from the sides. The general appearance of the valley of a vigorously eroding stream is one of unfinished ruggedness and angularity.

Canyons attain spectacular development in the mountain and plateau regions of the West, where the conditions of high elevation and aridity are realized in unusual degree. The master canyon-maker of the North American continent is the Colorado River. With an abundant supply of water from the heavy snowfalls of the mountains of Wyoming, Colorado, and Utah, and a course which takes it across a dry plateau which in places reaches an elevation of more than 9000 feet, the Colorado and its tributaries have eroded a vast system of canyons beyond all comparison. The section of the river extending from the mouth of the Little Colorado to the Grand Wash Cliffs, almost at the Nevada line, is known as the Grand Canyon. This segment is about 200 miles in length, varies from four to around sixteen miles in width, and has a maximum depth of more than one mile. The ruggedness of this type of valley is well exemplified in the rough, broken walls of the Canyon, and in the mountainous masses of rock rising

Great Northern Railway



Cascades, Glacier National Park, Montana. The cascades are produced in this case by water falling over the exposed edges of sedimentary rock. When such strata dip slightly in a downstream direction, conditions are provided which are very favorable to the development of cascades, which may be considered intermediate between rapids and falls.

from its depths. These features can be studied in the photograph reproduced on page 75.

Another magnificent canyon is that of the Yellowstone River. It is about 1000 feet in depth, and almost perfectly V-shaped. Its banks are resplendent with outcropping rocks of many colors, particularly of the buff-yellow which has given the region its name. (See illustration, p. 78.)

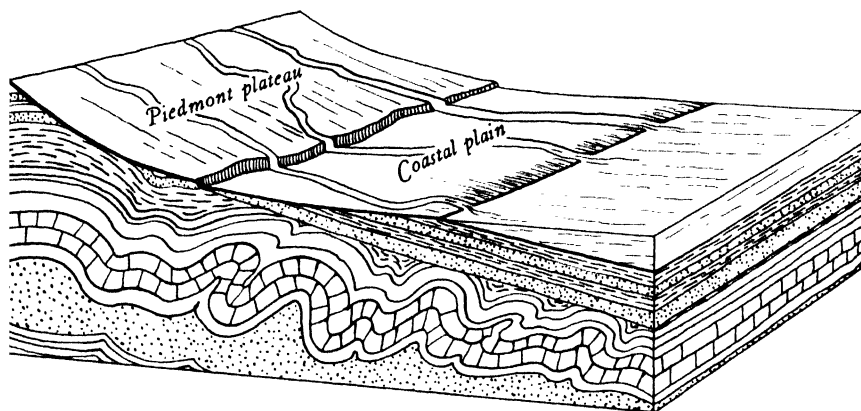
Every major stream flowing out of the Rocky Mountains has carved a canyon. The Royal Gorge of the Arkansas, the Black Canyon of the Gunnison, Flaming Gorge of the Green River, the gorge of the Shoshone, the canyons of the Wind River, Big Horn, and Snake are but a few examples.

It should not be supposed that canyons are not to be found in the more humid sections. They occur in such regions occasionally, often in response to changed conditions, such as the recent removal of vegetation, which may have given special stimulation to the erosive processes.

Note the remarkable system of canyons shown on the Soda Canyon, Colorado, map, p. 447.

Falls and rapids. Not only does the cross section of a valley such as those described present a picture of incompleting erosion, but this condition is also suggested by its longitudinal profile. Irregularities and angles exist in its bed, and some of these may be of such magnitude as to constitute falls or rapids. A rapid is an increase in gradient of noticeable, though moderate, extent; it differs from a fall only in that it is less steep. Small falls are termed cascades, and often occur in groups or series, such as that pictured on page 80. Cascades of this kind may be intermediate stages marking the wearing down of falls into rapids—or, in some cases, the reverse.

Although falls may result from original irregularities which have not been removed by erosion, or from the deposition of material within stream channels, the majority are due to unequal erosion on the part of the stream itself. Streams crossing lines of division between hard and soft rocks are likely to develop falls. The soft, poorly consolidated materials that make up the Atlantic coastal plain, for example, lie adjacent to the much older and harder rocks of the Piedmont plateau. Many falls and rapids have been developed by the comparatively rapid



Section through the fall line, showing how erosion of the junction of the Piedmont plateau and the adjacent coastal plain results in a row of falls and rapids.

erosion of the softer rocks east of this division line, which is known in consequence as the fall line (see diagram above).

The diagram on page 79 depicts one of the most favorable conditions for the formation of falls or rapids—the existence of hard strata overlying or alternating with softer strata. If the rocks dip upstream, falls very often result; if downstream, rapids. Niagara Falls, for example, drops its enormous load of water (93,000,000 gallons per minute) over the edge of an 80-foot ledge of limestone which overlies much softer shales and thin-bedded limestones. The water, falling 160 feet, washes away the less resistant formations, undercutting, or *sapping*, the limestone, which from time to time breaks off and plunges into the chasm below. Thus the fall retreats upstream, at a rate estimated to average between three and five feet per year. As it retreats, the fall becomes steadily lower, for the limestone stratum forming the brink dips slightly upstream.

Igneous rocks injected among sedimentaries along a stream's course may cause unequal erosion resulting in falls. Two such injected masses have produced the splendid falls of the Yellowstone River. The Upper Yellowstone Falls has a drop of 110 feet; the Lower, 310 feet. The Lower Falls is shown in the illustration on page 78.

A common cause of falls is to be found in erosion which has proceeded more rapidly in a main valley than in its tributaries, leaving the points of junction between the two suspended at a level above

that of the main valley (see *hanging valleys*, p. 186). Water leaving the mouth of the tributary plunges downward as a fall, as shown in the illustration on this page. Examples of falls of this type are to be seen in Yosemite Valley. Here Bridalveil Fall drops 620 feet; the Upper Yosemite, 1430 feet; and the Ribbon Fall, a total of 1612 feet.

River terraces. The sides of valleys are not infrequently lined by rock terraces. The common cause of these structures is stream erosion through horizontal layers of differing hardness. A stream cuts a steep-walled valley rapidly through the softer layers. When a hard layer is encountered, down-cutting continues, but at a much slower rate, while the banks of the valley weather, wear, and wash into the stream. By the time the more resistant stratum has been cut through,

(Left) *One-half mile of falling water in Yosemite Valley. The channel through which the water enters is a hanging valley, Yosemite having been greatly deepened and widened by glacial erosion.* (Right) *Potholes in process of formation in Seven Falls Canyon, near Colorado Springs. The sculpture of these falls is governed by strong cracks in the rocks.*

Missouri Pacific Railroad

Missouri Pacific Railroad





U. S. Geological Survey, photograph by L. W. Stephenson



U. S. Geological Survey, photograph by W. C. Alden

(Left) *Potholes on the Rio Grande River, Maverick County, Texas.* (Right)
Detail of a Pothole.

the softer rock above it will have been reduced to low slopes. Terraces of this kind attain their best development in arid or semiarid regions.

If another weak formation underlies the hard layer, rapid erosion will begin again, with undercutting of the hard stratum, which will break off in angular blocks. In this way, hard strata come to form cliffs, soft ones slopes, as shown on page 87. The cliffs and terraces of the Grand Canyon are very obvious examples, as can be seen by consulting the photograph reproduced on page 75.

Potholes. Slight irregularities in the bottom or sides of a vigorous, rapidly eroding stream may throw the water into a swirling eddy. Sand and gravel dragged into this whirl grind out a shallow, circular depression. This basin catches more sand and pebbles, which aid in its further enlargement; it may by this means become wider at the bottom than at the top. Cavities of this kind (see illustrations on this page) are called *potholes*, *giants' cauldrons*, or *kettles*, although the term kettle is more commonly applied to basins of glacial origin. Potholes may be but a few feet across, or they may have diameters of several yards; in some instances they are of greater depth than width. They may develop in either igneous or sedimentary rock.

Pothole grinding is an important phase of erosion in many mountain streams, in some being the chief process by which the stream bed is lowered. Many such streams show curved, polished surfaces which are the remains of old potholes.

Potholes are of common occurrence below waterfalls, in which

situations they are frequently referred to as *plunge basins*. An excellent example is provided by the potholes being formed in Seven Falls Canyon, Colorado, pictured on page 83. Mountain lakes not infrequently occupy such depressions.

Oxbows. More numerous than potholes, though often of temporary duration, are the basins produced by rivers through the cutting off of portions of their own channels. Mention has been made of the wide bends or *meanders* that are a normal feature of the later life history of a river. Water passing around these curves travels most rapidly along the outer edges, causing erosion at these places; ultimately the stream may cut through the neck of land separating one meander from another, abandoning a curving section of its channel, which is then called an *oxbow lake*. The process of forming an oxbow lake is shown in the diagram on this page. Reference to the Bayou Sara, Louisiana, map on page 435 shows how a basin of this kind was formed by the Mississippi. It is evident that at one time the river flowed through the channel of False River, but finally broke through the neck of land between Grand Swamp and Alligator Bayou.

Several oxbow lakes are also to be seen in the process of formation on the Edmond, Oklahoma, map (p. 440). In sections 24 and 25 water flows intermittently through a new channel which cuts off three meanders, which we may assume will eventually be completely separated from the river, like the one in section 19.

The meandering stream shown at the right can gradually wear down the entire level of the valley floor. Having lost much of its downward erosional force, due to the flatness of the land mass, the stream bed is confined to a shallow, serpentine course. The stream often intercepts its own winding loops. Sometimes the islands thus formed are slowly eroded and become part of the stream bed. Sometimes, however, the old channel is abandoned, forming an oxbow lake.





New Mexico State Tourist Bureau

High elevation and brightly colored horizontal rocks combine to make the region of northern New Mexico and Arizona a land of many spectacular mesas, buttes, and monuments. The well-known mesa shown here is located west of Albuquerque.

Erosional remnants. As an elevated land mass in a temperate, semi-arid climate wastes away under the ravages of erosion—largely the headward working of rivers and creeks—it breaks up into many strange and grotesque forms. Around its edges may be found an array of shafts and towers, castlelike prominences and pillars, some of them raggedly attached to the cliffs, some standing alone. These structures, tall and narrow and exposed to erosive and weathering forces on all sides, do not endure for long; hence they become rarer with distance from the parent plateau. Larger masses of rock, however, which have escaped destruction because of superior hardness, special protection, or greater distances from the invading streams may be found scattered for mile upon mile across the country formerly occupied by the original highland.

Small remnants of this kind are called *monuments* or “hoodoos.”

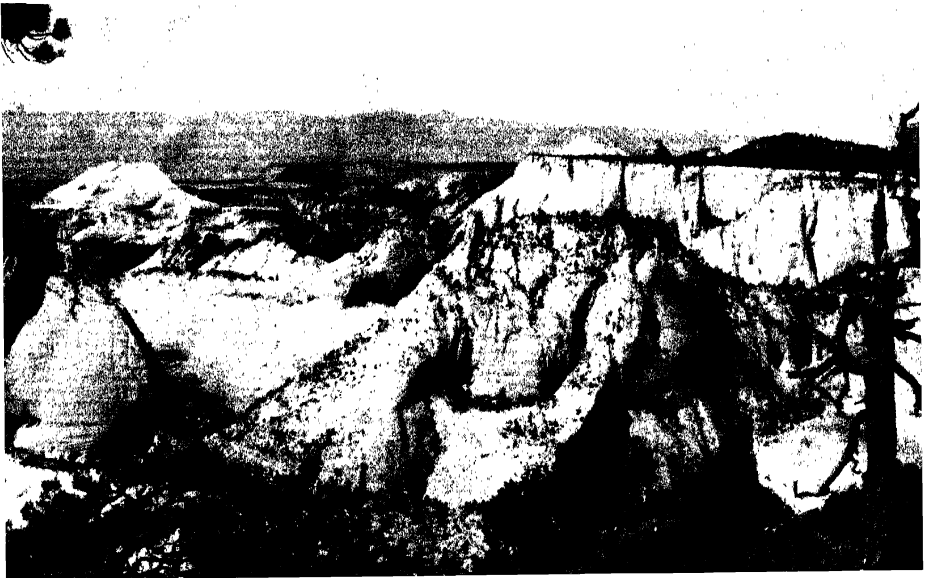
They may consist throughout of a material more resistant to erosion than the surrounding rock, or they may owe their preservation to the protection afforded by a cap rock which is part of the remains of a once continuous resistant layer. In claylike formations containing boulders, rain and gully erosion may leave the boulders perched upon high columns of the softer rock, which are thus sheltered from the effects of erosion acting from above.

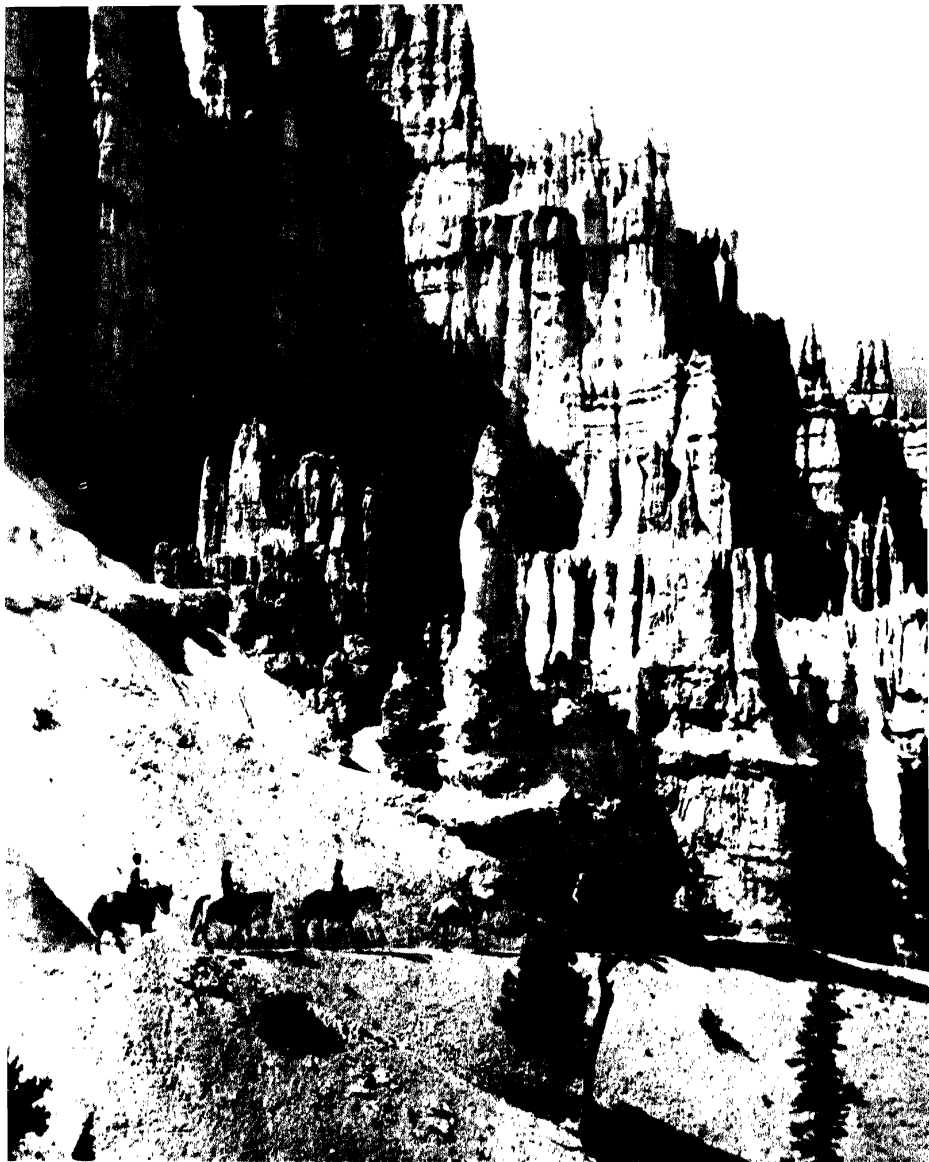
If the rocks of a country undergoing such dissection are horizontal sedimentaries of varying hardness, some of them of fairly resistant character, numerous patches of considerable area will be left standing. These remnants will be flat on top, for they are capped by a hard stratum, ordinarily the same that forms the top layer of the retreating plateau; they are therefore called *mesas*. Another condition which very commonly gives rise to mesas is the outpouring of lava upon level ground. When erosive agents finally succeed in eating through this durable cover, or undercut it from its edges, they gnaw rapidly into the softer rocks beneath, dissecting the entire mass, leaving intact only scattered patches of tableland.

As the erosion of mesas is accomplished almost entirely by the undercutting of their resistant top layer, they shrink in area even as they grow in height with the general lowering of the surrounding country. At length so little of their upper surface remains that they

Conditions favoring mesa formation. Note how a resistant cap rock is producing flat-topped structures.

Union Pacific Railroad Photograph



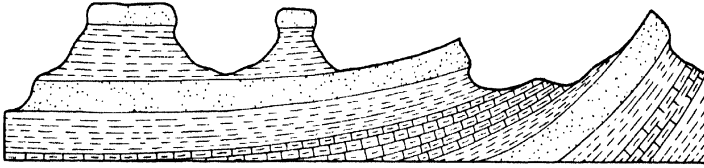


Union Pacific Railroad Photograph

Details of the erosion in Bryce Canyon.

no longer merit the designation "mesa"; their still flat-topped but outstandingly vertical remains are then termed *buttes*. (The term *butte* is loosely used in the West to designate any sort of large hill or mountain left standing after the erosion of the surrounding rock.)

No essential difference exists between the smaller mesas and the larger buttes, or between the smaller buttes and the more massive monuments (compare the illustrations on pages 87 and 345).

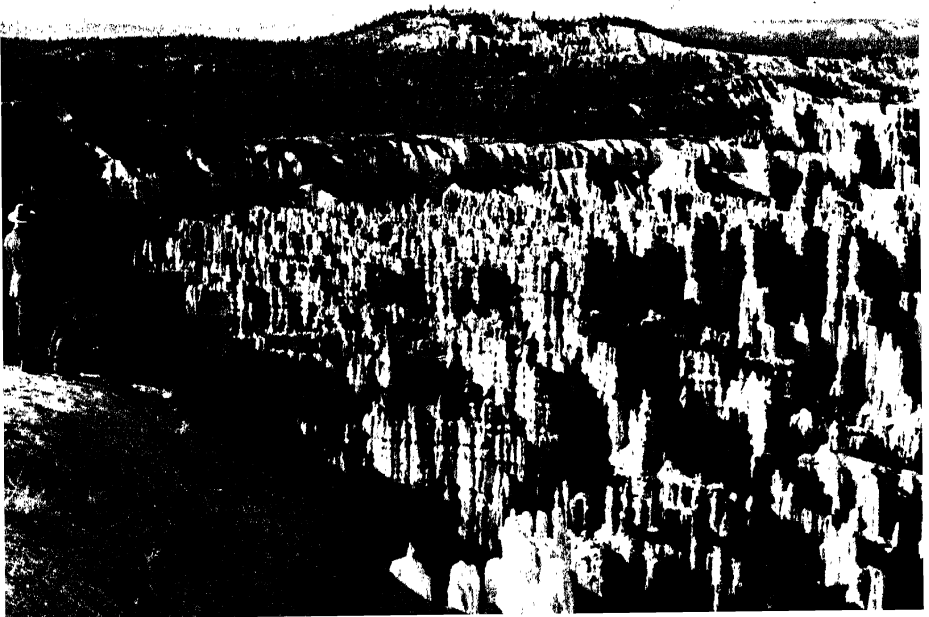


Effects of folding upon the topography of a region of high elevation; a hypothetical section adjoining mountains on the right, showing how erosion produces hogbacks, cuestas, buttes, monuments, and mesas away from the mountainous area.

The erosion of an area of tilted strata often results in the formation of long ridges, representing the outcropping edges of resistant rock layers. If the dip of the strata is slight, the resulting ridges will be unsymmetrical in shape, the steeper side facing away from the direction of dip. Such ridges are called *cuestas*; they attain conspicuous develop-

A magnificent result of rain and gully erosion in soft rock. Bryce Canyon, Utah.

Union Pacific Railroad Photograph





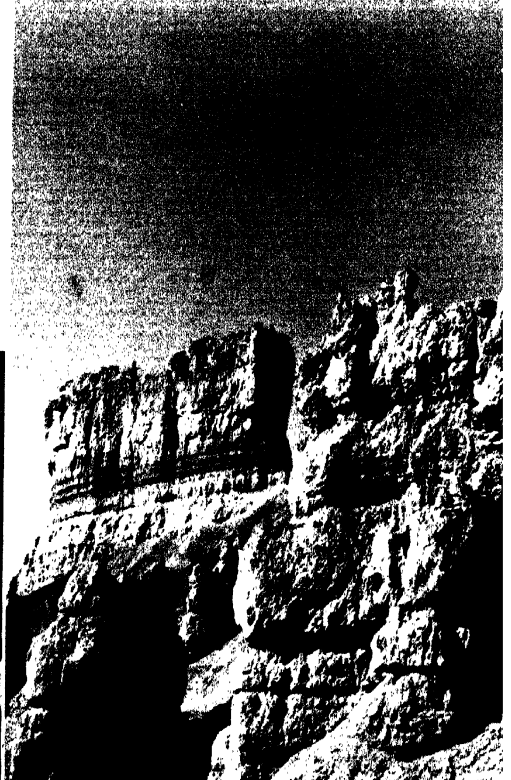
United States Geological Survey, photograph by W. D. Johnson

An erosional remnant in a stream bed. Unlike most structures of this shape, this mass of rhyolite is of the same hardness throughout. It has been shaped by the turbulent waters of the Owens River, California, which fluctuates over a very narrow range.

(Left) Awe-inspiring monuments of sandstone stand guard in Canyon de Chelly, northern Arizona. (Right) Tattered rock masses large and small linger for a time as erosion gnaws its way into the side of a retreating plateau.

United States Geological Survey, photograph by Hillers

Union Pacific Railroad Photograph



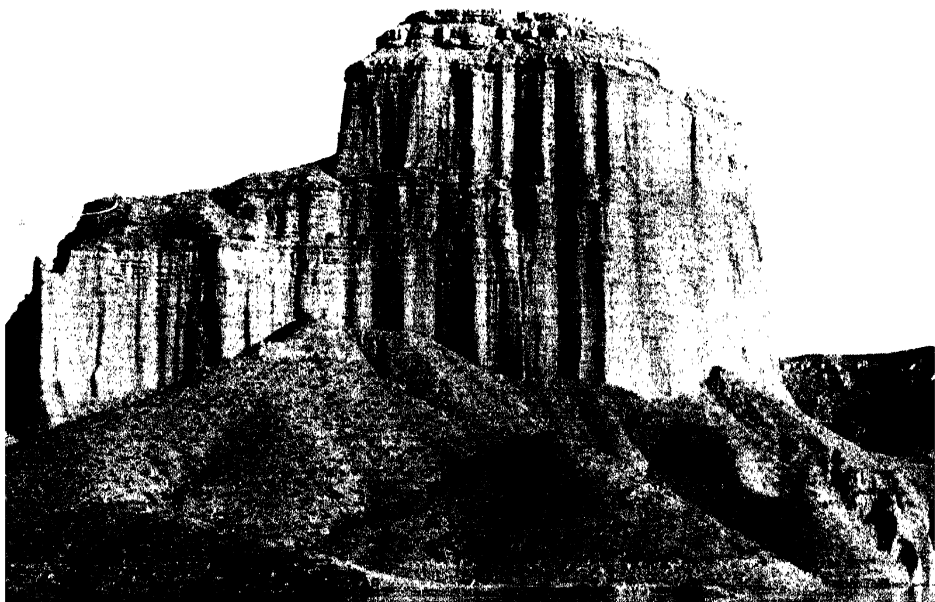


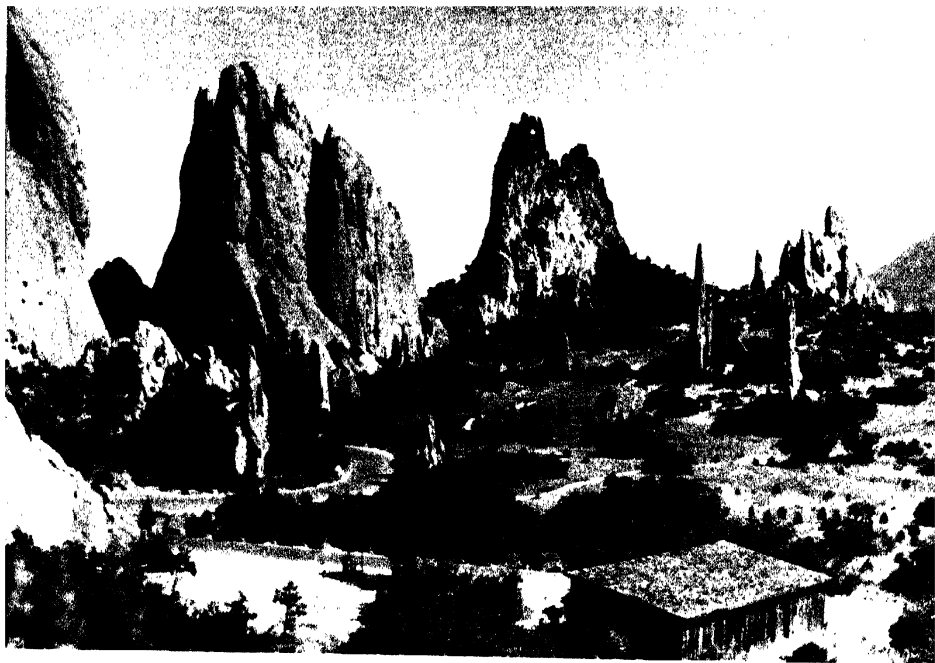
United States Forest Service, photograph by Jay Higgins United States Geological Survey, photograph by H. E. Gregory

(Left) *Remnants of a once vast plateau; note the horizontal attitude of the strata. San Juan National Forest, Colorado.* (Right) *Mitten Butte, Arizona.*

Temple Bar, an imposing butte on Lake Mead.

Bureau of Reclamation





Pikes Peak Information Bureau

The Garden of the Gods, Colorado. A strikingly picturesque region featured by vertical hogbacks of brilliant red sandstone.

A typical hogback in New Mexico.

United States Geological Survey, photograph by N. H. Darton





United States Geological Survey, photograph by H. E. Gregory

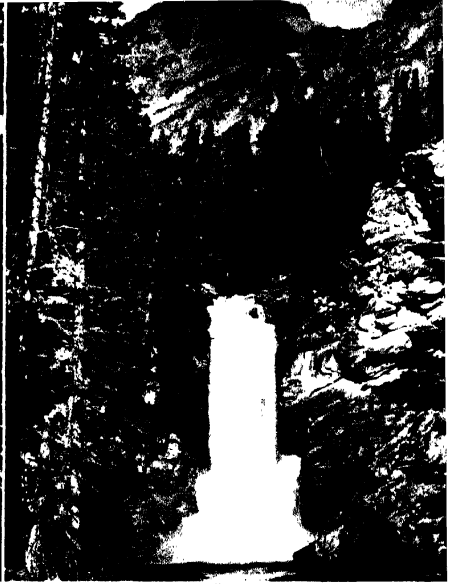
Showing natural bridge in process of formation through surface agencies, chiefly gravity fall induced by weathering.

ment in Arizona, New Mexico, and along the Atlantic and Gulf coasts. If the tilted strata dip at a high angle, there will be less difference in the angles of slope of the sides of the ridges, which are then termed *hogbacks*. The region of upwarped rocks around the bases of the Rockies in Colorado and elsewhere provides many good examples. In regions adjoining mountains, in which rock strata are gradually flattening out, hogbacks may occur near the mountains, cuestas farther away, and structures typical of horizontal strata at some distance; these relationships are indicated in the diagram on page 89. The reader is urged to study the photographs on pages 86, 87, 88, 89, 90, 91, and 92 in connection with the foregoing section.

Natural bridges. Among the more picturesque by-products of erosion are the wide variety of stone bridges which are left standing for a time during the process of reduction of a landscape by erosion. There are several kinds of these bridges, which consist principally of either limestone or sandstone remnants.



Norfolk and Western Railway



Great Northern Railway

(Left) The famed Natural Bridge of Virginia. Once thought to have resulted from the collapse of a cavern roof, it is now considered to be the product of underground stream erosion. (Right) Probably a natural bridge in the making. When the water from the upper stream finds its way through the rocks into the channel of the lower stream, a bridge will result. Glacier National Park.

The Rainbow Bridge of San Juan County, southeastern Utah, towers more than 300 feet above the stream which carved it.

Utah Department of Publicity



Perhaps the majority of natural bridges are the result of seepage from streams flowing over limestone beds into cracks in the underlying rock. The percolating water works its way along joints and bedding planes, dissolving rock as it moves, emerging at length downstream, in many cases below a waterfall. More and more of the water of the stream will be diverted into the underground channel, until at length there is no surface flow left. Erosion will then cease on the surface, but continue below, until part of the original stream bed becomes a bridge spanning the stream. The famous limestone bridge in the western part of Virginia appears to have been formed in this manner.

In the illustration on page 94 we see this process actually taking place along a stream in Glacier National Park. Here water has worked its way downward along joints some distance upstream, then horizontally along bedding planes.

Sometimes small bridges are formed during the process of pothole-grinding. Two adjacent potholes, which, it will be remembered, are often larger below than at the surface, may enlarge until they unite some distance underground, leaving a narrow strip of rock separating them and bridging the common cavity formed by their coalescence.

By far the finest of all natural bridges are the products of the action

Onachomo Natural Bridge, 55 miles west of Blanding, southeastern Utah, is a grand example of the sculpturing power of running water. Two other bridges of comparable size occur within three miles.

Utah Department of Publicity



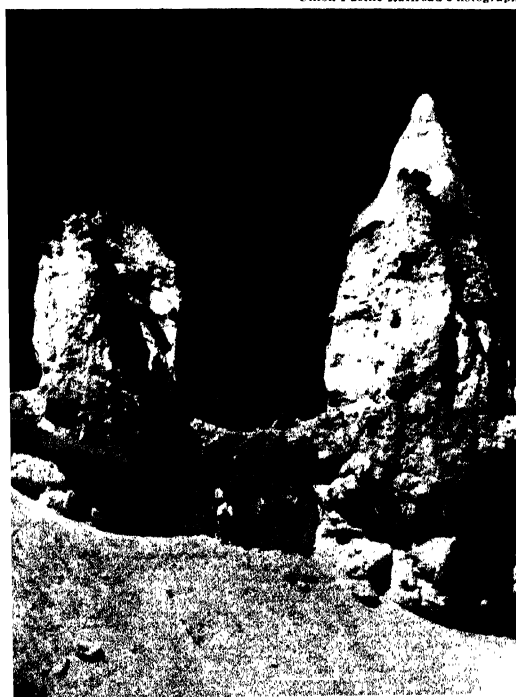
of streams in undercutting narrow divides between parallel canyons, or grinding openings through obstructions in their channels. The most striking examples of these structures are to be found in southwestern Utah, in a region so difficult of access that they have been viewed by but few persons. Of great size and matchless symmetry is the Rainbow Natural Bridge, shown on page 94, which has resulted from the work of a small tributary of the Colorado River. A few miles below the confluence of the Colorado and the San Juan, the flow of this stream was obstructed by a spur of white sandstone which jutted across its course from its south bank. Through this projection it cut its way, thereby carving out the famous "rainbow turned to stone," an arch 309 feet high, with a majestic span of 278 feet.

Northeast of the Rainbow Bridge stands a group of three other bridges of titanic proportions. Two of these, like the Rainbow, were formed by the perforation of projecting spurs; the third, by the undercutting of a narrow divide by a stream and one of its tributaries. One of these bridges is pictured on page 95.

TRANSPORTATION BY STREAMS

The stream's load. The reservoir from which the agents of transportation draw their tremendous loads is the surface mantle of

Union Pacific Railroad Photograph



A natural bridge in southern Utah, a result of the weathering and removal of softer rock above and below a more resistant ledge.

The carrying power of a stream increases very rapidly when the velocity of its current increases. In times of low water, diminishing streams drop most of their load, even their finer constituents, which form sand bars and mud banks. During flood seasons, these deposits are picked up by the increasing current and carried onward toward the sea. At such times the hydraulic force of some rivers becomes enormous, causing great damage. When in flood, the small stream shown at the right can easily move the large rocks lying upon its bed.



United States Forest Service

weathered waste. From it are picked up, directly or indirectly, almost the whole of the vast mass of fragmental material which is washed, blown, or carried toward sea level, ultimately to be made into rock again.

Most loose surface material finds its way sooner or later into stream channels. Runoff from rains is often the final factor in bringing rock waste into bodies of flowing water; but even in dry weather, streams may be turbid with silt which has been brought down to the water solely by creep and slump. Into the stream, too, pours the invisible load of dissolved solids which rainwash picks up from the soil. These materials, together with those which the stream itself rasps from its bottom and sides and the dissolved salts which ooze into the channel from the ground constitute the stream's load.

An idea of the immense volume of rock waste being transported from place to place by geological agents may be obtained from the following figures. According to the United States Geological Survey, the amount of material being moved from the United States into the sea in *solution* is approximately 270,000,000 tons annually; this is equivalent to the removal of an average of 90 tons of soluble matter—largely potential plant foods—from each square mile of surface per



Soil Conservation Service

The results of rainwash during a single storm.

year as a result of solvent action. The surface of the United States, according to these figures, is being lowered at the rate of one foot in 30,000 years from this cause alone. It is estimated that nearly twice this amount of material, some 513,000,000 tons, is carried to the sea each year in the form of solid matter. The reduction of the United States resulting from these combined processes amounts to one foot in slightly more than 9000 years. This calculation does not take into consideration the quantity of material moved along the bottoms of stream beds, which is in the aggregate considerable in the higher parts of many stream courses, but negligible near their mouths.

The Mississippi River alone has been estimated to transport 136,000,000 tons of matter in solution and 340,000,000 tons in suspension annually. Among North American rivers the Colorado ranks second to the Mississippi in the quantity of material carried.

The transporting process. Most of the load of the average stream—clay, silt, or fine sand—is carried in suspension. The concentration of this sediment may reach as much as 50 per cent in some streams. These finer particles may be kept off the bottom almost indefinitely by small upward-moving currents. Small pebbles are rolled along the

bottom, or progress with a jumping motion. The larger and more angular rocks in a stream bed are pushed downstream bodily by the force of the water; in many streams such rocks are transported for the most part during floods, remaining stationary at other times.

The chief factor in determining a stream's ability to carry sediment is its velocity. The relationship between its carrying power, or *capacity*, and its velocity, however, is not a simple one, and cannot be expressed in a definite formula. Much depends, for example, upon the sizes of the rock particles contained within the stream channel; if these are large, the stream may not be able to move them at all, while if the increase in speed should pass a critical point for the size of many of the contained particles, the increase in capacity would be far greater than would be the case if the size of all particles were below this limit. The shape, depth, and amount of load of a stream also influence the rate of change in capacity brought about by increase or decrease of velocity. Nevertheless, it may be said that under most conditions a change in the velocity of a stream is accompanied by a disproportionately large change in its ability to move sediment.

The *competence* of a stream refers to the size of the individual particles which it is capable of moving. The approximate sizes that can be moved by water traveling at various speeds is given below:

Rate of Flow in Miles per Hour	Size of Particles That Can Be Moved	Rate of Flow in Miles per Hour	Size of Particles That Can Be Moved
.15	Clay	1.00	Coarse gravel
.25	Fine sand	1.50	One-inch pebbles
.50	Coarse sand	3.00	Two-inch pebbles
.65	Fine gravel	5.00	Eight-inch boulders

In a stream in which the volume is large in relation to the amount of material carried, the maximum size of the particles which the water can move may be considered to vary with the sixth power of the velocity. Thus in such a stream doubling the velocity may enable the stream to move particles 64 times as large as before, and tripling the velocity should increase the competence 729 times. Actually, there are several factors which may modify these results.

The velocity of a stream may be doubled by a fourfold increase in gradient, or an eightfold increase in volume. Floods sometimes increase the velocity of the Mississippi by more than four times; the

flow of some rivers has been known to increase over twenty times. Under such conditions, the power of a river becomes very great indeed; torrents have torn up railroad tracks, washed away steel bridges, and moved concrete weighing thousands of tons.

DEPOSITION FROM STREAMS

The conditions which are most commonly responsible for causing streams to deposit all or part of their sediment are the following:

1. Decrease of gradient
2. Overloading
3. Increase in width of channel
4. Change from straight to crooked channel
5. Obstruction in channel
6. Entrance into body of quiet water
7. Evaporation

Several of these factors, of course, may and often do co-operate in the formation of a deposit. Often, however, the location, composition, and structure of deposited sediments are characteristic of conditions under which they were laid, linking them to one or more causes.

Stratification. The arrangement of sediments in definite layers is nearly always a feature of water-laid deposits. Wherever the surface upon which sedimentary deposits are being formed is locally rough or irregular, layers of small areal extent ranging in thickness from less than an inch to ten feet or more will be lapped over the obstructing irregularity, resulting in a succession of small strata which lie at an angle to the general stratification of the formation of which they are a part. Such irregular or nonparallel stratification, shown in the illustrations on pages 101 and 103, is termed *cross-bedding*, *false-bedding*, or, if the strata are exceptionally thin, *cross-lamination*. Cross-bedded strata invariably dip downstream, or in the direction of the current which deposited them, and are usually concave on the upper surface. Because of the irregularity of the mass over which they have been laid or because of the inconstancy of the agent which deposited them, they are often laid at varying angles and in different directions, presenting a very confusing pattern.

Cross-bedding is a common feature in continental deposits, resulting from the action of either wind or water. The cross-bedding shown in this picture accumulated in the West under very arid conditions and was formed by shifting winds of greatly varying force or strength.

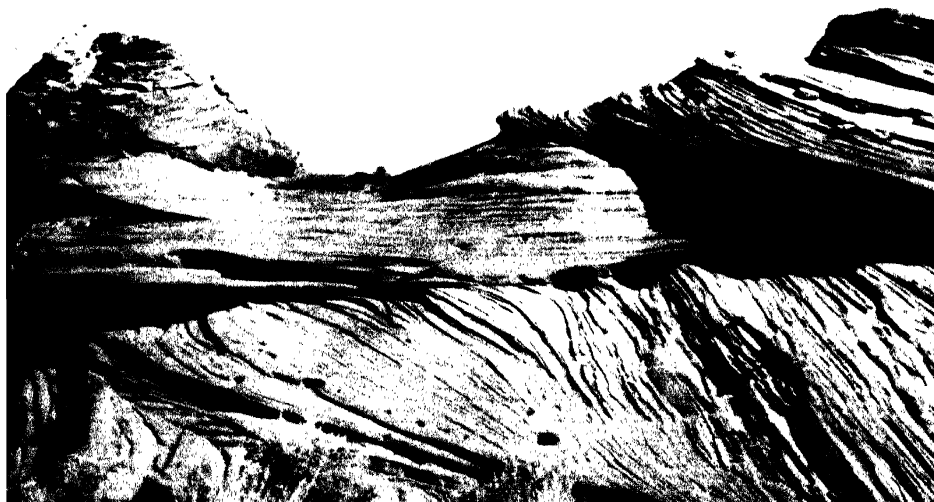


United States Geological Survey, photograph by H. E. Gregory

Piedmont deposits. Around the bases of many mountains and plateaus, and in many basins, such as Death Valley (illustration, p. 344), are to be found deposits which were made by streams as a result of rapid decrease in their gradients brought about by emergence from the highlands upon a more nearly level terrane. These deposits slope down-stream, and spread out fanlike away from the parent streams; from their shape they are called *alluvial fans*, or, if steep, *alluvial cones*. Such structures, which may vary in diameter from a few inches to many tens of miles, are very roughly stratified, containing particles of all sizes; boulders weighing up to seventeen tons are reported to have been so deposited by torrential mountain streams. These deposits fill the stream channels, forcing the water to find new courses; for this reason streams which are building alluvial fans usually break up into a number of smaller streams known as distributaries.

Intensely cross-bedded sandstone. Arizona. This sandstone (the Coconino) was largely wind-deposited.

United States Geological Survey, photograph by H. E. Gregory



As in a talus slope, the surface of a fan is concave, the degree of inclination decreasing regularly downstream. Like that of the talus slope, also, is the almost completely clastic character of the materials which constitute the fan. In the latter structure, however, imperfect stratification and some degree of rounding of the constituents can be detected, as well as the presence of former stream channels. The fan usually contains some material which has fallen upon it, while the talus slope contains some brought in by running water.

Along the bases of mountains alluvial fans often merge along their lateral margins to form long, continuous bands of sediment called

An extremely young gully actively eroding loose tuffs in the San Juan Mountains, Colorado. An alluvial fan is being formed at the base of the mountains.

United States Geological Survey, photograph by Howe



Stream-channel deposits: their origin is revealed in this cross-section by the gravelly, poorly-sorted character and cross-bedded structure. Streams flow at greatly varying rates during the year and in different parts of the stream channel, carrying different amounts and different kinds of material; they often leave their stream channels and form new courses, making temporary deposits on their beds; they erode one bank of their channels and deposit on the other bank. These are some of the factors which contribute to the heterogeneous, poorly-stratified nature of stream deposits. Can you think of others? This photograph was taken in a gravel pit, excavated in a long, winding ridge leading away from the Wichita Mountains, Oklahoma. Hard gravel, deposited in the ancient stream bed, resisted erosion more successfully than the surrounding territory. What was once a stream bed is now a ridge.



Photograph by H. E. Brown

piedmont alluvial plains. The High Plains, extending eastward from the Rocky Mountains for several hundred miles, are of this character. Around the Sierras alluvial deposits are also extensive, although in some cases their slopes are virtually imperceptible. These piedmont deposits usually attain their best development in arid or semiarid regions, where the depositional effect of reduced gradient is augmented by that of evaporation or of the sinking of water into the ground. Mountain streams in well-watered regions are generally able to carry away most of their loads.

Small alluvial fans are also of frequent occurrence at the mouths of tributary valleys entering valleys of lower gradients than their own. An example is shown on page 102.

Valley deposits. Even in the absence of any sudden decrease in gradient, streams lay down sediments within their own channels. These deposits may be of a temporary character, or they may be more or less permanent. In the upper sections of a stream's course, deposits of boulders, pebbles, gravel, or coarser sands usually predominate over finer sands and muds, which are carried downstream, often to be dropped toward the stream's mouth. In a stream which pursues a fairly straight course, there is also some tendency toward lateral segregation of particles, those of larger size finding positions near the center of the stream, finer ones migrating toward the sides; this separation is due to the generally more rapid motion of the water in the middle section.

It is near the headwaters also that angularity is most pronounced among the sediments laid down by a stream. Here, as farther downstream, the rounding effects of stream transportation are most noticeable on the larger fragments which, if of homogeneous character, become more and more nearly round with increasing distance from their source. Very small grains may show little rounding effect even after a long journey, and such minute angular particles may sometimes be encountered in abundance in deposits quite near a river's mouth; their retention of angularity over long distances points to their transportation in suspension rather than in frequent contact with the bottom.

In the intermediate and lower sections of its course a stream normally wanders more or less from side to side, swinging across its valley in meanders of a few feet to several miles in width, the size being directly proportional to the size of the stream. Water on the outside of each curve moves with a higher velocity than that on the inner side; as a consequence, deposition occurs on the inside of each curve, especially at the apex and along the portion facing upstream. These processes are illustrated in the diagram on page 106 and by the photographs on pages 105 and 107. At the same time, water piles up against the outer and downstream sections of each curve, with resulting erosion at these places. It is believed that there is here a downward movement of the water which, if it reaches bottom, results in deepening the channel; presumably the water then moves toward the opposite bank, carrying with it sediment which it in part deposits.

In these ways alluvial sediments are strewn in sheets along the



Photograph by H. E. Brown

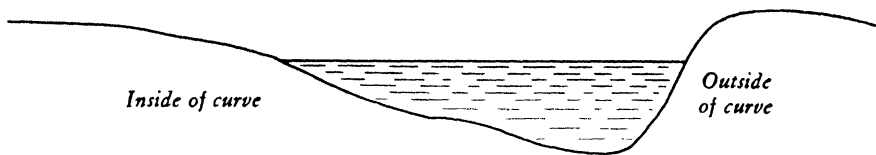
An old river finds its load too much to bear, and spreads it out across its valley, while sediment dropped within the channel causes the stream to break up into smaller streams.

Yampa Canyon, Dinosaur National Monument, Utah, shows the effects of erosion on the outside of curves and deposition on the inner sides. This photograph also shows one of the causes of valley widening—undercutting of banks, followed by slumping.

National Park Service, photograph by George A. Grant



inner and upstream margins of meanders. Erosion continues on the outer and downstream sides, with the result that meanders migrate



Cross section of meandering stream, showing typical shape of channel.

both laterally and downstream. The deepened parts of the channel next the convex sides of the bends migrate with the stream itself, and these become catch basins for rock fragments, largely the coarser pieces which the stream rolls or pushes along the bottom. Thus the bed of the stream channel becomes gradually covered by layers of poorly sorted sediments, accumulations of different kinds alternating frequently, and showing conspicuous cross-bedding. A typical stream deposit may be studied in the illustration on page 103.

All streams which have reached a mature or old stage do not meander. Some are so heavily loaded that much sediment is dropped bodily in their channels, forcing their waters to break up into numbers of smaller streams, which reunite and again diverge, with much water moving beneath the accumulating sands. Streams of this kind, of which the Platte is a typical example, are called *braided streams*.

River *sand bars* are accumulations of sand within a stream's channel, deposits resulting either from the conditions outlined above or from some irregularity or obstruction on the bottom. Sand is washed up and over such a bar, falling into the section of quiet water protected by its downstream face, which is steeper than that exposed to the current. Bars, which are markedly cross-bedded as a result of this mode of deposition, migrate slowly downstream.

During the later stages of a stream's development, low gradients and heavy loads combine to make floods common occurrences. At times of high water when velocities are greatly increased, torrential currents scour out some of the channel deposits laid down during periods when the water was low, sometimes to a depth of fifty feet or more. When the water gets high enough to spill out of the channel, it spreads this and other material over the flats which have resulted from the erosional and depositional activities of the meandering stream,

already described. Thus is formed a broad, flat surface, the river's flood plain. It is the product both of horizontal erosion by a migrating river and of deposition by the same stream, both at times of low water and of flood. At first the flood plain is no wider than the belt which includes the stream's meanders; eventually it may become many times as wide.

Examination of the section of the Donaldsonville, Louisiana, map on page 439, showing a section of the Mississippi and adjacent flood plain, reveals that the land is higher next the river than farther away, standing at 25 feet above sea level close to the channel and declining to less than 5 feet in the swamps a few miles away. This is a condition common in old rivers, and results from repeated overflows.

During a flood the water within the river channel is flowing rapidly, and is fully able to transport all of its load. Water covering the flood plains outside the channel, however, is moving slowly, and has but little carrying power. Water carrying material out of the channel onto the valley flats becomes less and less competent to move sediment as its distance from the channel increases; deposition of sediment, therefore, is heavy close to the river, becoming less as the sides of the valley are approached. The coarsest material is thus laid down nearest to the

This stream is cutting into a steep 20-foot bank on the outside of its curve, depositing on the inner side.

Soil Conservation Service, photograph by Jules Renaud



river channel, where the flood plain is built to its highest level, while away from the river the deposited sediments become steadily finer and thinner.

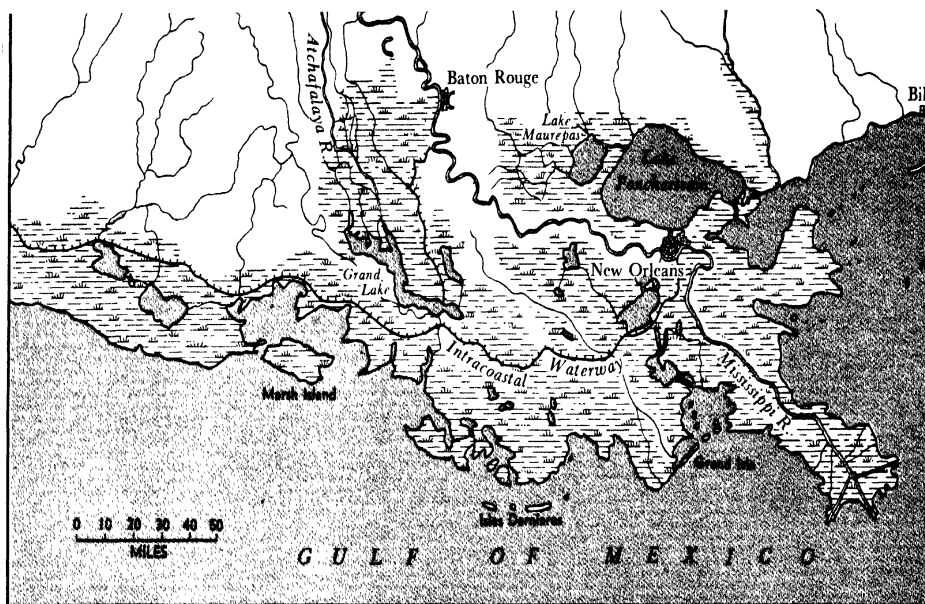
This comparatively high ground bordering the river channel constitutes *natural levees*. As these are built higher and higher by successive floods, the bed of the river is also raised, until it may lie at a considerable elevation above the land back of the levees. This land is usually swampy, since there is often no way for water to escape through the levees into the river. Tributary streams may flow parallel to the main river for many miles before finding a means of entrance into it.

In some cases *river terraces* are the products of alternating erosion and deposition. If after the building of a flood plain the power of down-cutting returns to an old river as a result of increased volume, decreased load, or other cause, the stream will cut actively into its flood plain, portions of which may escape destruction and remain standing as terraces. Later, when the down-cutting effort has spent itself, another flood plain may be built at a lower level than the first, and the process may be repeated until several terraces line the valley, one above another. A terrace of this origin may be seen in the illustration on page 111.

Flood-plain deposits are marked by their variability from place to place, but in general they may be said to consist of flat-lying sheets of clastic sediments, especially of the finer sorts, crossed occasionally by narrow bands of coarse, cross-bedded sands and gravels which mark the sites of former stream channels. Ripple marks may be found crossing the flats at right angles to the motion of the current; these marks are asymmetrical in cross section, their steeper sides facing downstream, thus revealing the direction of the current which produced them. Flood plains are favorable locations for the development and preservation of mud cracks and the imprints of raindrops.

Flood-plain sediments of fairly humid regions are usually dark in color when first deposited, as the result of the inclusion of considerable organic matter. If allowed to dry out, this coloration fades as the organic material is destroyed by bacterial action, while the oxidation of iron compounds changes it gradually to brown, yellow, or red.

Such fossils as may be found will be principally those of land plants and fresh-water animals, although the remains of land animals are occasionally preserved under flood-plain conditions.



The Mississippi delta, 12,000 square miles.

Delta deposits. Upon flowing into the sea or other body of standing water, many streams spread their loads out in broad, fan-shaped structures known, from their resemblance to the Greek letter of that name, as *deltas*. A delta shows certain similarities to an alluvial fan. Both structures are the result of the sudden checking of a stream's current; they are of much the same shape, although the outlines of the delta are often greatly modified by waves or currents; and in both cases the depositing stream divides into numerous spreading distributaries. In a typical delta these distributaries build up natural levees which to some extent keep their currents confined, as a result of which long, fingerlike processes are built out into the water. Between the channels of the distributaries fine sediment is spread out, largely, in the lower sections of the delta, through the action of sea waves and currents. This flat land between the channels contains numerous small lakes and swamps, which leave their characteristic deposits superimposed upon, or included within, those of the delta.

The structure of the typical delta can be seen in the diagram on page 112 and in the photograph, p. 113. In front of the advancing delta, particles of the finest size are slowly settling to the bottom. These accumulating deposits, which serve as the foundation upon

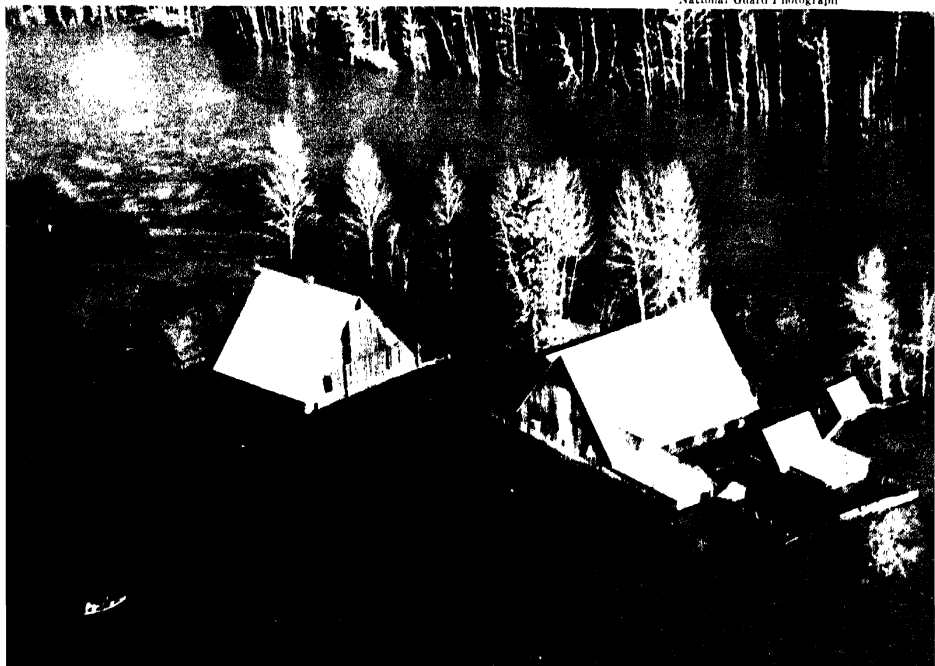


Norfolk and Western Railway

The Shenandoah Valley, with its broad flood plain and meandering river.

At times of flood alluvium is spread over the valley floor, successively finer material being carried farther and farther from the river channel, thus building up a flood plain. The relatively large quantity of coarse material deposited near the channel is built up into natural levees.

National Guard Photograph





United States Geological Survey, photograph by W. C. Alden

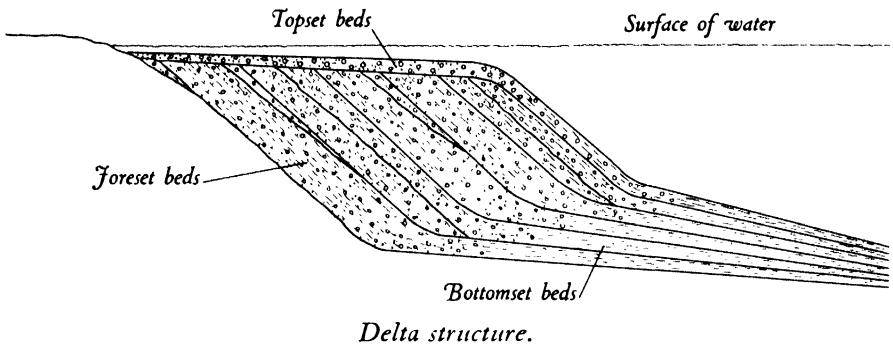
A river terrace in central Massachusetts. This terrace is the remnant of a former flood plain.

The natural levees along the lower Mississippi are generally dry, while the lower land on either side is too swampy for general agricultural use. Near New Orleans.

Official United States Army Air Corps Photograph



which the main body of the delta is later laid, constitute what are called the *bottomset beds*; these are actually marine deposits, and are



laid parallel to the sea bottom—nearly horizontally, in the ordinary case. Upon them, much coarser sediments are laid down, being poured over the edge of those previously deposited, and forming the *foreset beds*; these may lie at a high angle, 30° or more, to the bottomset beds. Across the surface of the foreset beds the river and the sea work over sediment and spread it out to form the *topset beds*, which are inclined seaward at about the same angle as the lower section of the stream's flood plain, with which they imperceptibly merge. The topset beds resemble flood-plain deposits in character, consisting, on the landward side, of clays, silts, organic matter, fine sand, and sometimes even gravel. Mud cracks and raindrop impressions may form above water, and fossils of land plants and animals and of fresh-water organisms are not infrequently preserved. In the seaward direction these characteristics are supplemented or supplanted by those of more typically marine conditions.

The structure described is much more likely to be realized in a lake delta or in one of very small size than in one of great dimensions built into the sea. In a large delta each distributary acts independently, building a delta of its own, and thus complicating the picture. In addition, the shape and structure of the deposit at the river mouth are constantly modified by marine agencies.

The Hwang River of China has built an enormous delta of more than 100,000 square miles into the Yellow Sea. The delta of the Nile is of about one half that area. The Mississippi delta extends for 12,000 square miles, and is growing outward into the Gulf at the ex-



United States Geological Survey, photograph by W. C. Alden

A cut through a delta deposit, showing the foreset and bottomset beds.

ceptional rate of a mile every sixteen years. Many of the larger deltas of the world appear to have been sinking during recent geological times; some of them are known to be many hundreds of feet in thickness, deep borings yielding bits of wood, old soils, fossils of shallow-water organisms, and similar evidences from far below the present surface.

The distribution of deltas is determined by the load delivered by the rivers, the strength of ocean waves and currents, the depth of the water, and the state of stability of the coast line. The Atlantic seaboard, for example, is almost if not quite devoid of deltas, partly because of the existence there of strong ocean currents, partly because of recent subsidence of much of the coast line.

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VI · GROUND WATER



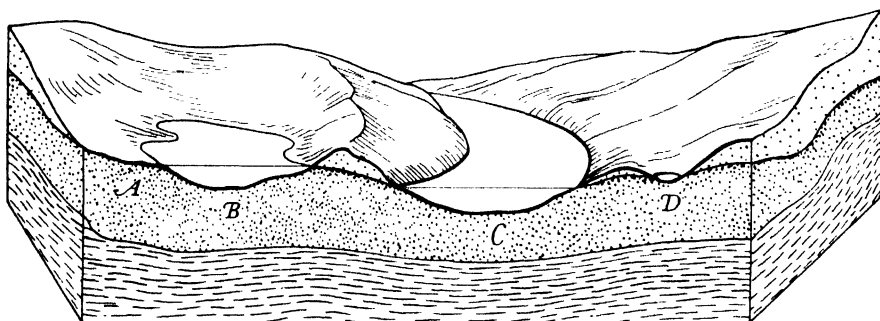
Among the pores and crevices of the upper rocks of the crust is a small amount of water of the utmost importance to man and to other dwellers on the land surfaces. Most of this water originally fell upon the earth as rain or snow, later finding its way into the ground. Some of it may never have been above the surface of the earth at all, having been from the time of the earth's formation a constituent of the rocks, from which it was released by melting and crystallization. This ground water, important from both economic and scientific standpoints, should be understood in its relations to the rocks in which it moves, before a study of its application to human affairs is undertaken.

Ground water is classified according to its origin. Water which has fallen to the earth from the atmosphere is designated as *meteoric* water, and that which has issued from the rocks and remained underground is known as *magmatic* or *juvenile* water. Water enclosed in sedimentary beds at the time of their formation may find no avenue of escape into other formations and so may remain within the original beds for indefinite periods of time; such water is known as *connate* water. The salt water found in petroleum-bearing formations is presumed to be sea water trapped in the strata at the time they were deposited. The term connate is also applied to magmatic water which still resides within the igneous rock within which it was formed.

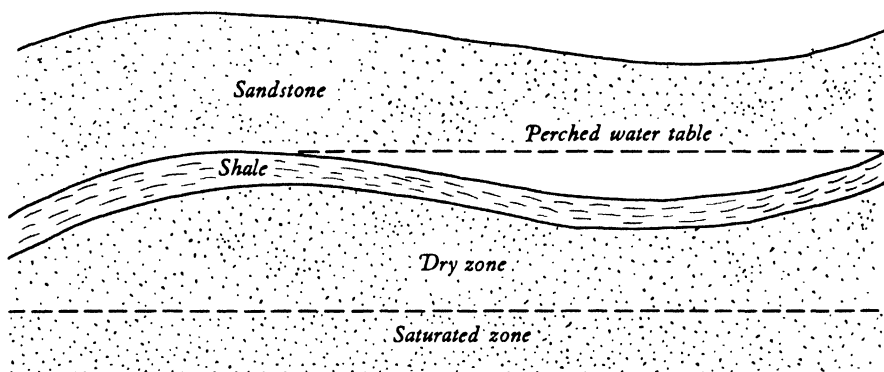
DYNAMICS OF GROUND WATER

Porosity and permeability. All rocks near the surface of the earth are more or less porous. The average amount of pore space present in surface sedimentary rocks is close to 5 or 10 per cent of the volume of the rock, although in some cases it is much greater—40 per cent or more. Even the finest-grained igneous rocks contain some pore space, perhaps no more than one part in several hundred of rock. It is within these pores that ground water exists; only in rare instances is it found in underground streams or lakes.

The behavior of ground water, however, is determined not so much by the total porosity of the rocks as by their *effective* porosity, which depends upon the sizes of the openings present and upon the extent of their connections. Water will, for example, enter and even rise into openings of a certain rather definite small diameter, a property known as capillarity. Coarse-grained sandstones, especially when poorly cemented, allow water to pass through them readily, although their pores may be too large to produce any marked capillary effect. Clays and shales, on the other hand, while they may themselves be saturated with water, offer great resistance to the passage of water through them, because of the attraction existing between their closely spaced particles; such rocks are described as *impervious*. Limestones, although



The relation of the water table (heavily dotted area) to the surface of the land and to various bodies of water: (A) spring, (B) lake, (C) permanent stream, (D) swamp.



Water in considerable quantity may be held above the true water table by impervious layers.

containing little pore space, are quite generally affected by fractures, and are therefore permeable to water. Igneous rocks may be permeable for the same reason.

The depth at which ground water exists is undetermined, but it is believed to be comparatively shallow. In some deep mines water has been encountered in the upper layers of rock, but has been absent from those at deeper levels.

The water table. In most places rocks near the surface of the earth do not contain much water. In this region water, except following rains, generally exists in the form of a film around grains of rock. It is this water that is drawn upon by the roots of plants during dry weather. But at some depth below the surface—and in some places at the surface—ground water may be found in such abundance that it completely fills all the pores among the rock particles. From this region of saturation it rises by capillary action into the drier soil above.

The surface beneath which the rocks are saturated with water is called the *water table* or *ground-water surface* (some authors limit the designation *ground water* to the water existing below this surface). The water table may intersect the surface of the land in places, producing springs, lakes, swamps, or rivers; but it usually lies at depths of several feet, sometimes hundreds of feet, below the top of the ground. The water table tends in a general way to correspond in shape to the surface of the ground above it. Following recent or prolonged rains it rises, more so under the uplands than under the valleys, thus tending to approach the contour of the land surface. During long rainless periods it slowly subsides, again chiefly under the uplands, becoming more nearly flat. The relation of the water table to the surface of the land above it and to various kinds of bodies of surface water can be seen in the diagram on page 116.

Movements of ground water. Water "seeks its own level," whether upon the surface or within the earth. Upon first sinking into the ground it ordinarily makes its way straight downward, unless deflected by impervious rocks. When the water table is encountered, movement is usually slowed down and changed in direction. Because of the inclination of the water table to flatten out under the influence of gravity, water below this surface moves, usually at a very slow rate,



Soil Conservation Service

Leafy plants give protection against raindrop erosion. They absorb the impact of the drops against the soil and allow the water to trickle gently to the ground. They also hold back much water until evaporation can take place. In addition, plants prevent rainwater from forming little channels or rivulets by the profusion of their stems, and their roots bind the soil firmly together, thus resisting erosion. By this means, run-off is reduced, the water table kept high, and both droughts and floods prevented.

in the direction of the slope of the water table, which may or may not coincide with that of the land surface above it.

In regions of especially soluble rock, cavities may be formed which permit such rapid movement of water as to be described as a flow. Water may also move at a fairly rapid rate, perhaps several feet a day, through loose sands, such as those occurring below or alongside a river channel. But in general it may be said that a movement of ground water amounting to one mile a year is to be regarded as exceptional; more often, a period of from two to twenty years would be required to traverse this distance.

All water in the ground above the water table is called *vadose* water. In the vadose zone permeability has been greatly enhanced by weathering. Below this region permeability decreases downward, and with it the freedom of movement of the ground water. At the greatest depths at which free water exists, practically no movement occurs. Some of the stagnant waters of this region are connate waters.

Man and the water table. The importance of man as a geological agent has long been recognized. The full significance of the changes he has brought about in the earth's crust, however, and the effects which these changes must inevitably have upon his own destiny, have

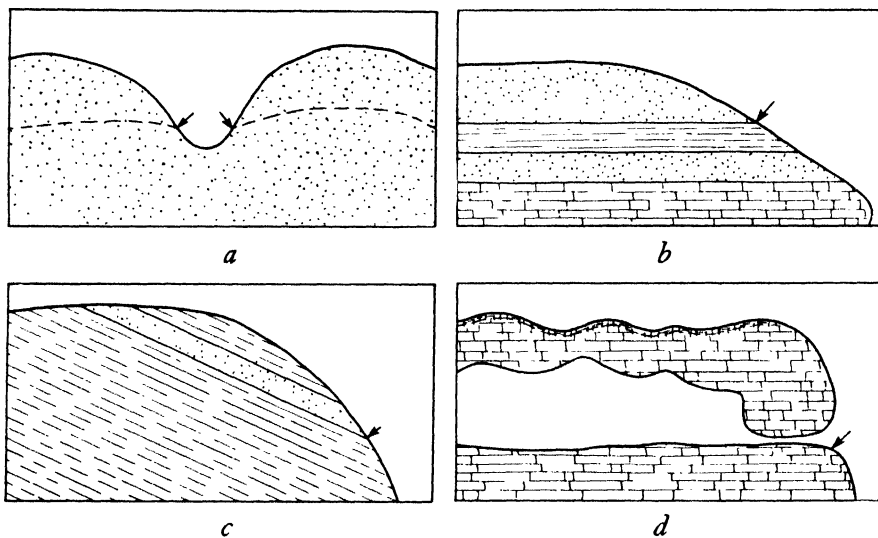
only very recently received serious attention. Mention has already been made of the effects of human activities in the promotion of weathering; far more striking are the effects of certain such activities upon erosion and upon the position of the water table. These latter changes are to be attributed chiefly to four processes: deforestation, cultivation, overgrazing, and pumping.

In its natural state, the earth's mantle of vegetation retards the runoff of rain water and permits a large proportion of the rainfall to seep into the ground. In consequence, the water table stands relatively high. Springs issue from hillsides, and from the beds of streams. Under these conditions the flow of water in streams is more or less steady the year round. During seasons of heavy rainfall much water is prevented from becoming runoff by shrubs, trees, and leaf mold, while during drier parts of the year streams are kept flowing by the seepage of ground water into their channels.

Vegetation protects the soil against wind as well as water. This scene from the Nebraska sandhills region shows in striking manner how sharply erosion may be retarded by a vegetative covering.

Soil Conservation Service





Several kinds of hillside springs. (a) Springs produced in homogeneous rock where water table intersects ground surface. (b) Spring occurs when course of descending vadose waters is interrupted by impervious layer. (c) Water enters and descends through porous layer, emerging as a spring. (d) Spring in a limestone formation.

When the natural vegetative cover is removed, the first result is usually increased runoff. Water falling upon the earth immediately flows over the surface to lower levels, eroding the land, scarring the hillsides, silting reservoirs and low-lying farm lands. Erosion by wind, especially in the drier sections given over chiefly to cattle raising, is of course also encouraged. The immediate results of deforestation may be seen in the photograph on page 72.

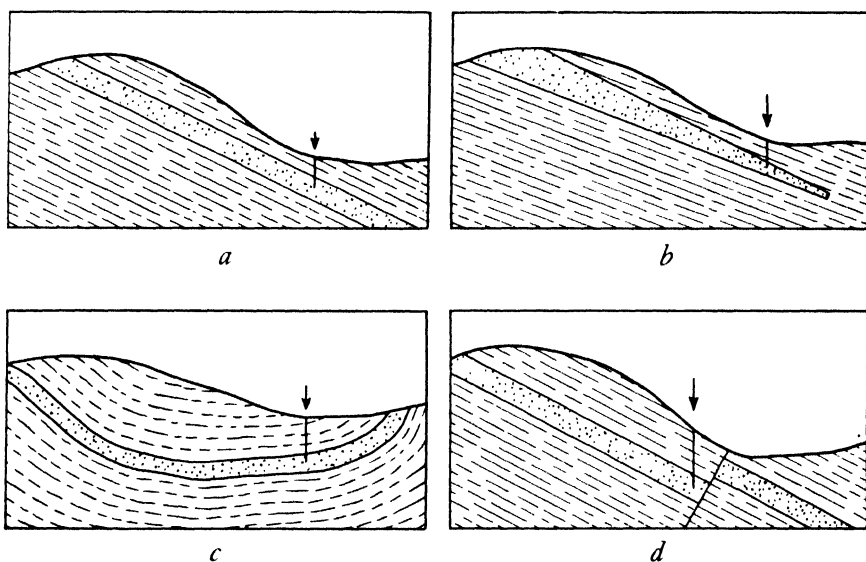
Valleys developed during periods of more regular stream flow are then inadequate to drain their denuded watersheds. Floods occur, increasing in severity year by year. Farm land is swept away, or buried beneath flood-borne loads of sand and silt.

As the runoff increases, less and less rain water is left to seep into the soil. The water table gradually falls. Springs dry up, streams become intermittent, wells go dry. When the flood season is over, drought ensues. Agricultural production falls off, followed, very likely, by the clearing of more land, thus intensifying the condition that menaces the world's greatest industry.

An economic problem of the most serious character has been pre-

sented by the lowering of the water table in certain sections by excessive pumping. In the Imperial Valley of California, parts of Arizona, the Texas panhandle, and some other regions in which irrigation is extensively practiced, the water table has been sinking in localized areas at a rate which may amount to several feet a year. It has been estimated, for example, that at certain points in Arizona and Texas water is being taken out of the ground ten to fifteen times as rapidly as it can be replaced by natural means. This situation will demand a revision of current agricultural practices in the immediate future.

A number of cities also face a critical shortage of water. At some places on the Pacific coast the withdrawal of ground water has permitted a subterranean influx of water from the sea, which has extended inland for a distance of several miles.



Springs of the artesian type. (a) Water moving through porous layer encounters less resistance in rising through fissure than in continuing against increasing rock pressure. (b) Rock layers are normally lenticular in shape. In this case water is forced to rise in fissure because of hydrostatic pressure developed by water at a higher level in the porous reservoir. (c) Here water may reach the surface if the concavely bent aquifer is saturated to a level higher than that of the top of the fissure. (d) The rocks have been broken and offset in such a manner that water in the upper part of the aquifer has been trapped, and, if under sufficient pressure from water at higher levels, will rise through the fissure.

It is hardly too much to say that the fate of humanity is concentrated in the upper six or eight inches of soil, and in the water which comes to this soil from above and below. The maintenance of the present social order, if not the actual survival of man himself, depends upon an intelligent study of the management of these factors. In order to live man must continue to farm the soil. But he must also protect it; there is not enough left even now to meet the needs of the world's rapidly increasing population. Such measures as terracing, plowing under of every possible particle of organic matter, gully control, protection of grasslands in the grazing districts, and restraint in the use of the earth's underground reservoir of water will go a long way toward preserving the soil and its water for generations of the future.

PHYSIOGRAPHIC EFFECTS OF THE ACTION OF GROUND WATER

Permanent and intermittent streams. Streams whose channels are too shallow to penetrate the water table will run dry after they have discharged the surplus water from rains. Since the water table rises and sinks in correspondence with the supply of water reaching it from the surface, a stream will also be intermittent in its flow if its bed lies below the upper level of the water table, but above its *dry-weather* level. To carry water the year around, a stream's channel must be deep enough to intersect the level below which the water table never sinks. The same principle applies to the productivity of wells. (See, however, the diagram at the bottom of page 116.)

Springs. The occurrence of springs is a certain indication that rain has been falling somewhere at a higher level. Sometimes the source of the water is evident, as where water seeps into a permeable layer

United States Geological Survey, photograph by N. H. Darton



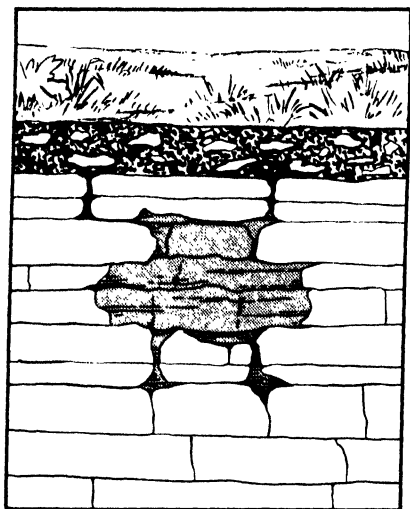
Artesian well. This common phenomenon occurs in regions of water-containing sedimentary rocks, where the pressure of water standing at higher subterranean levels forces the free-flowing but lower water sources to seek the common, higher level.

underlain by an impervious one on a hilltop and emerges at some point down the slope; these conditions are indicated in the illustration on page 120. In numerous cases, however, the elevated region in which the water finds entrance to the earth is many miles from the site of its reappearance; it might in such an instance rise vertically through a fissure to emerge upon a plain. Springs of this type are called *artesian springs*; their occurrence demands the presence of a permeable reservoir rock surrounded by impervious material, and a fissure extending from the reservoir to the surface. The rise of the water is brought about by hydrostatic pressure exerted in the reservoir layer by water standing at a higher level, as shown in the illustration on page 121. The emerging water can be lifted to a height that is not quite equal to the level of the top of the water in the reservoir, the difference being due to the friction between water and grains of rock through which it passes. Geysers are intermittently eruptive springs, best described in connection with volcanic phenomena.

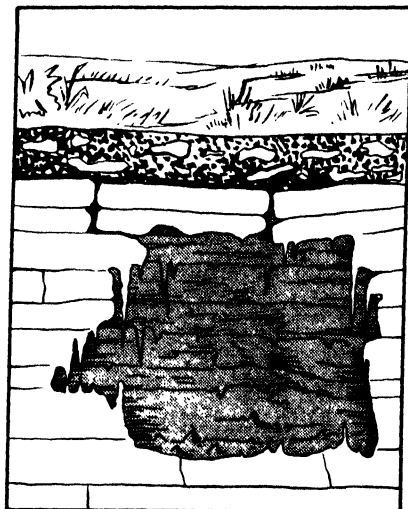
The water of springs possesses certain distinctive characteristics. It is usually much clearer than natural surface waters, because its slow movement through the ground filters out practically all solid impurities. Its temperature, in relation to that of surface waters, is inclined to be moderate and constant; the waters of some springs, however, are warm or hot, owing to contact with hot rocks, often deep in the earth. Spring waters further differ from those of rivers and lakes in that they usually contain a larger percentage of dissolved matter; springs especially notable in this respect are frequently called mineral springs.

Solution basins. In regions underlain by thick beds of limestone, funnel-shaped or irregular depressions in the surface are often to be seen. These basins are *limestone sinks* or *sink holes*; they are produced by the solvent action of water upon the limestone. Water seeping downward along joints gradually dissolves and carries away the rock, until a sink is formed; this is especially likely to occur where the course of the descending water is more or less concentrated, as at the point of intersection of two joints. The soil above a sink which is being formed in this manner settles downward gradually, frequently producing a depression of very symmetrical shape.

Limestone sinks are also formed by the sudden collapse of the rock



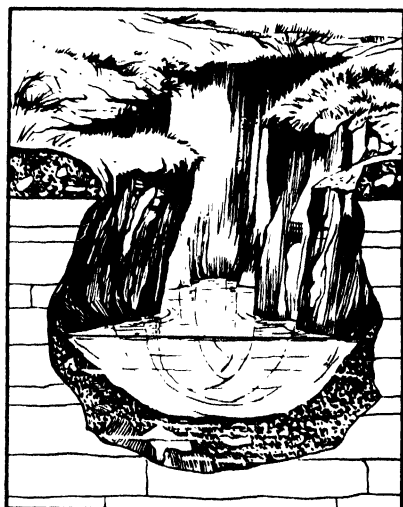
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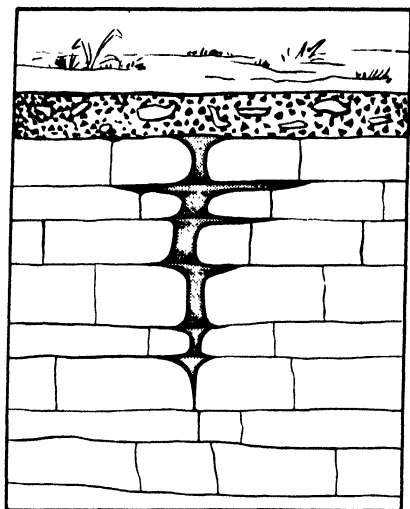


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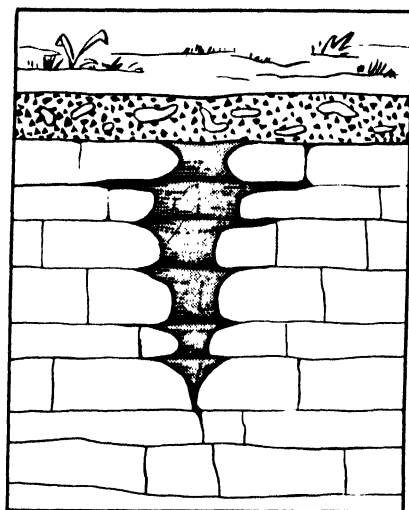
The development of a limestone sink through the collapse of a cavern roof.

which forms the roofs of caverns. Sinks of such origin are generally much more irregular in outline. Both these modes of origin are illustrated on this and the facing page. Contrast in the appearance of the two kinds of sinks may be studied in the illustrations on page 126.

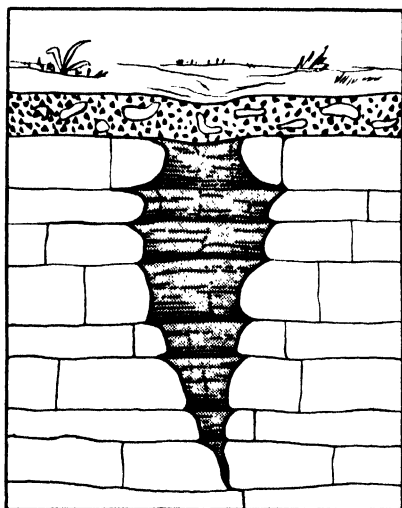
Sinks are of all sizes. Some are but a few inches across, others cover many acres, or even several square miles. Sometimes they coalesce to



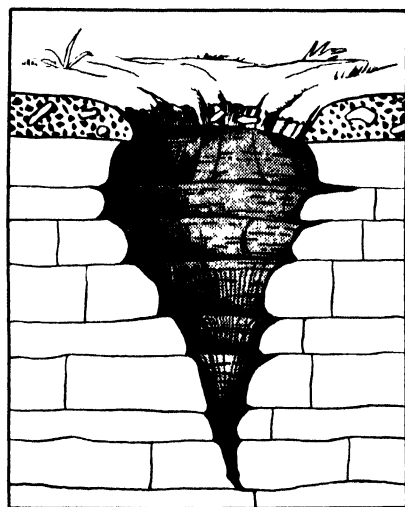
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The development of a limestone sink through solution along a fissure.

form elongate solution valleys. In most cases, water drains out into underground channels, but some sinks contain water, either because their outlets have become clogged with sediment or because the water table has risen to a level above their floors. Northern Florida contains many lakes occupying sink basins.

Limestone sinks frequently occur in large groups, which present a



United States Geological Survey, photograph by W. T. Lee



Photograph by H. E. Brown

(Left) *A sink in gypsum rock near Carlsbad, New Mexico. The roof of this cavity collapsed suddenly, leaving a sink hole about 60 feet deep.* (Right) *A typical limestone sink in southern Indiana.*

rather striking topographic aspect. Such a group is to be seen on the Princeton, Kentucky, map, p. 446.

Natural bridges produced by ground water. A considerable number of natural bridges have been formed primarily by the solvent action of ground water. Adjacent depressions resulting from solution at and near the surface (see page 123) may drain into subterranean cavities, which may become enlarged and merge into a common opening. The rock on the surface separating the depressions thus becomes a bridge.

Some stone bridges may be formed by the collapse of parts of the roofs of caves, leaving intervening parts intact. This mode of formation, however, is far from common, and clear-cut examples of its action are hard to find.

Caverns. In a few instances, caverns are known to have been produced, at least in part, by the action of running water. Cementing substances holding sand grains together are often dissolved by water moving along a crack, and if sufficient current is present, the loose grains may be carried away. Enlargement of the fissure permits the water to flow with increased velocity, resulting in accelerated erosion, and eventually a cavern of some size may be developed.

All the large caves of the world have been the result, principally, of solution by ground water. Limestone, dolomite, marble, gypsum, and rock salt are all readily soluble, and their removal may produce cavities of considerable size in the earth. Limestone, being by far the

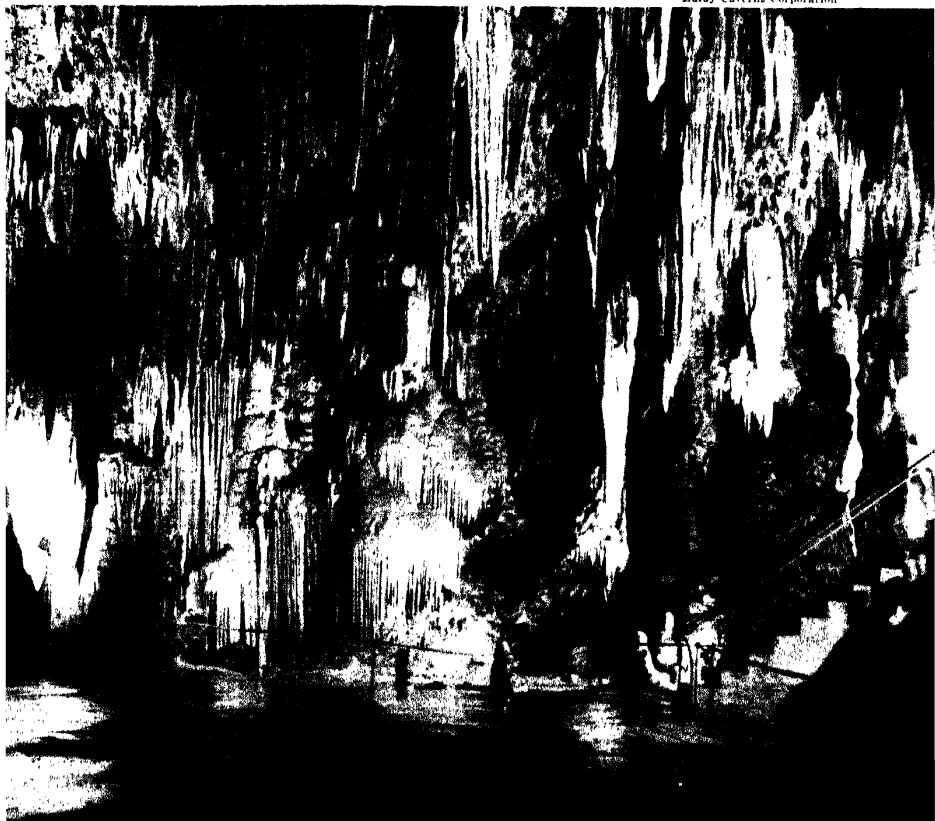
most abundant of these soluble rocks, is the only one which plays a very significant part in cave formation.

The water producing caves generally descends from the surface through joints or fissures in the rock, although instances are known in which solution has been effected through the action of carbonated waters rising from below. Water frequently shows a tendency to follow cracks and to seep along bedding planes, in this way forming long tunnels of comparatively small diameter. Large cavities or "rooms" may result from differences in solubility of the rock, local fracturing on an unusual scale, or differences in the water supply or in the amount of carbon dioxide in the water. If alternating strata of differing solubilities are present, galleries at several levels may be formed, perhaps with intercommunicating shafts.

One of the most remarkable cave regions in the world comprises about 8000 square miles in Kentucky, southern Indiana, and northern Tennessee. (See the Princeton, Kentucky, map, p. 446.) This section is underlain by a nearly horizontal bed of limestone with a thickness

Luray Caverns, Virginia; the product of the extensive solution of limestone.

Luray Caverns Corporation





Santa Fe Railway

Stalagmites in Carlsbad Caverns. Giant Dome, left of center, one of the world's largest stalagmites, is 62 feet high and 16 feet in diameter. Twin domes to right. Rate of growth has been estimated at about 1 inch per century.

of several hundred feet. This stratum contains little clay or sand, and is consequently almost entirely soluble. Out of it have been dissolved literally thousands of caves, of which the most celebrated is Mammoth Cave, near Bowling Green, Kentucky. The area including this great cavern is only about ten miles in diameter, yet it is honeycombed by at least 150 miles of tunnels. Although lacking the striking ornamentation of some caverns, Mammoth is noteworthy for its several streams, lakes, and waterfalls. Other important caves of the eastern half of the country are Wyandotte and Marengo of Indiana (both in the same limestone beds as Mammoth), and Luray of Virginia. Many smaller and less spectacular caverns exist, some of them of special interest for historic or other reasons; among them might be mentioned Mark

Twain Cave, near Hannibal, Missouri. Another important cave section is the state of Florida.

In the West, interest in caves centers around vast and beautiful Carlsbad Cavern, in the southeast corner of New Mexico. This cave, dissolved out of the limestones of the Guadalupe Mountains, is famous alike for its great size and for its magnificent ornamentation (see page 128). It is more than 1300 feet in maximum depth, and contains a single room 350 feet high, 625 feet wide, and 4000 feet long. Hundreds of stalactites depend from the roof, while huge stalagmites rise from the floor, some to a height of almost 100 feet.

Wind Cave in South Dakota is of special geological interest, in that its excavation is believed to have been brought about by ascending, rather than by descending, waters.

DEPOSITS BY GROUND WATER

Since ground water transports almost no sediment, deposition by this agent is practically limited to material which is laid down from solution. The principal causes of such deposition are (1) evaporation of the solvent, (2) decrease in temperature, (3) decrease in pressure, and (4) change in the chemical nature of the solvent, as through the loss of carbon dioxide or an increase in acidity.

Water rising to the surface of the ground through capillary action may evaporate, leaving an incrustation of mineral matter (such as the "desert limestone" of New Mexico and Arizona). Hot waters, rising through fissures, deposit mineral matter when temperature and pressure fall, or when the chemical constitution of the water is altered, filling the fissures and forming veins. When springs emerge at the surface, the escape of carbon dioxide into the air may precipitate limestone, either in the form of travertine or as the more porous form known as *calcareous tufa* or *sinter*. *Siliceous sinter*, or *geyserite*, a variety of opal, is a deposit formed around the mouths of some hot springs and geysers.

Below the water table deposition is also in progress. Here water saturated with mineral matter slowly lays down part of its dissolved load among the grains of rock.

Concretions. Concretions are nodules of mineral matter, varying widely in size and shape, occurring in sedimentary rock in which they



Oklahoma Geological Survey, photograph by E. S. Perry

Chert concretions in Boone Limestone, near Seneca, Missouri. Silica, which is soluble in alkaline waters, may sometimes be gathered into solution over large areas and then concentrated and precipitated in certain places where chemical conditions are favorable. As a general rule, concretions are composed of one of the minor constituents of the surrounding rock. Chert or flint concretions are quite common, therefore, in some limestones. The siliceous deposits shown at the left were introduced along cracks or bedding planes.

have been deposited from solution. Some are of microscopic size, others many feet across. They may be spherical, disc-shaped, cylindrical, or highly irregular. Not infrequently they resemble some animal or vegetable form, such as a potato or acorn. Occasionally they suggest some man-made implement. Barite "roses" occur in Oklahoma and elsewhere. Concretions often show a concentric structure, and many, though not all, are constructed around a central nucleus, such as a mineral grain, the body of an insect, or a particle of vegetable matter. Some idea of the wide variability in the shapes of concretions may be obtained by reference to the illustrations on this and the facing page.

In composition, concretions are most commonly of silica, calcite, or compounds of iron. Silica concretions (flint or chert) occur very widely in chalk and limestone. Concretions of calcite or iron are often found in sandstone or shale, while those of clay occur in many kinds of rock. Concretions are more common along bedding planes than embedded within strata, but occur infrequently along joints.

Some concretions were evidently formed at the same time as the rocks which enclose them, since they may contain fossils of the same age as these beds, and may also interrupt or influence the course of the stratification. Others were laid down subsequently to the formation of the enclosing rocks, although in most cases before the complete solidification of the latter.

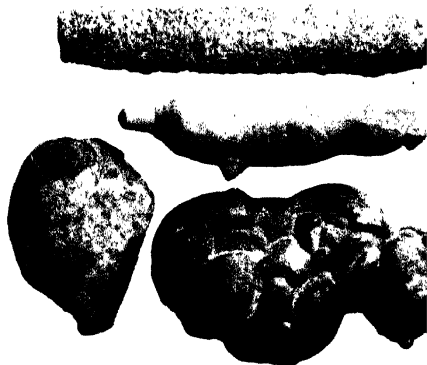
An interesting and unusual rock form is that known as *septarium*, in which numerous connecting cracks have formed and have been filled with mineral matter of another kind, usually quartz or calcite. Septaria are often called "petrified turtles"; the reason for this term becomes apparent upon consulting the photograph shown on this page.

Deposition in cavities. *Agate* is a banded form of quartz, apparently originating from the deposition of successive layers of the ma-



Illinois Geological Survey

A geode lined with quartz crystals.

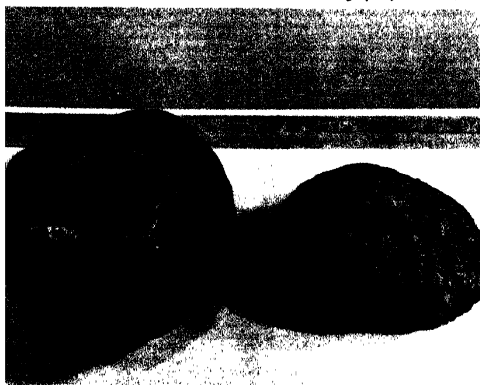


Illinois Geological Survey

Concretions are of many shapes and sizes.

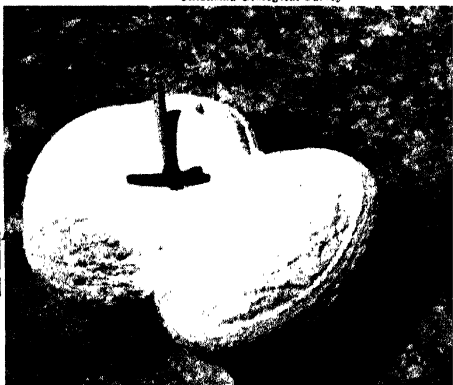
Septaria, masses of mineral matter crossed by many small veins.

Photograph by Hal Owen



Large double concretion. Beaver County, Oklahoma.

Oklahoma Geological Survey



terial on the walls of cavities in the bedrock. In many cases, the openings in which agate occurs are in igneous rock, the result of steam pressure.

Geodes are cavities which have been partly or wholly filled with inward-pointing crystals. Quartz and calcite are the most common minerals found in these situations. A typical specimen is pictured on page 131.

In this classification also are the *stalactites* (p. 127), which hang iciclelike from the roofs of caverns, and the *stalagmites*, which often rise from their floors. The former are produced when water, trickling through the limestone roof, emerges upon the upper surfaces of the opening, where it either evaporates or loses its carbon dioxide to the air; in either case its minute charge of calcium carbonate is deposited. The growth thus started is continued by more water, which runs, drop by drop, toward the tip of the structure already formed. Stalagmites are similarly formed by water dripping to the floor. Sometimes stalactites and stalagmites meet to form a pillar. Limestone is also deposited as sheets upon the walls of caves, as stone draperies, and as the peculiar, fingerlike growths known as *helictites*, which may repeatedly change their direction of development.

Replacement. While it is true that most solution takes place in regions near the surface and that deposition occurs chiefly at the surface or below the zone of weathering, both processes can take place at

Terracelike deposits of travertine. Carlsbad Caverns, New Mexico.

United States Geological Survey, photograph by W. T. Lee



Tree trunks of rock in the Petrified Forest, Arizona—a good example of the replacement of one material by another through the agency of ground water. The living tissue of the tree has been replaced by mineral matter. This material was not formed at its present level but was buried in a great depth of rock. As the rock was elevated and eroded, the petrified trees accumulated on the surface, being more resistant to erosion than the enclosing rock. Still more lie beneath the ground; wood has been uncovered in deep valleys 250 feet below the surface.



National Park Service, photograph by George A. Grant

any level at which water is present. Indeed, they may occur at the same place and at virtually the same time, as is demonstrated by the phenomenon of *replacement*. Whole crystals may be removed in solution by ground water and replaced by other mineral matter. Replacement affecting organic matter is called *petrification*. This process may affect shells, bones, or wood, leaving the original structure practically unchanged, but substituting calcite, silica, or some other substance for that originally present. Outstanding examples of petrification are to be found in the "petrified forests" of Arizona and Yellowstone Park, a portion of the former of which appears above. Here we see sections of petrified logs which were originally distributed through a considerable vertical distance within an embedding formation, the erosion of which has left the logs upon the surface.

VII · LAKES AND SWAMPS



Few large areas of the well-watered sections of the earth do not have lakes or swamps of one sort or another. Bodies of standing water are especially numerous in northern lands, as in the section of Canada pictured on page 202. They also occur in considerable numbers in many mountainous regions, and along the flood plains of old rivers.

The dimensions and general characteristics of these bodies of water vary greatly. In size they range from great lakes like the Caspian Sea to small ponds and marshlands. The composition of their waters is also extremely variable; the water of Crater Lake, for example, contains less than one one-hundredth per cent of dissolved solids, while in certain salt lakes the concentration of dissolved substances may reach 25 per cent or more.

Lakes contribute much to the welfare of man, moderating the climates of adjacent lands, regulating the flow of rivers to which they are connected, supplying water for cities and for industrial purposes, and providing a source of food and recreation. Lakes also perform a limited amount of geological work.

Some of the features of some of the world's notable lakes are given below:

Lake	Area in Square Miles	Maximum Depth in Feet	Altitude of Surface in Feet
Caspian Sea	170,000	3,200	-85
Lake Superior	31,810	1,180	602
Lake Victoria	26,200	270	3,800
Lake Michigan	22,400	870	581
Lake Huron	23,010	750	581
Lake Baikal	13,300	5,400	1,700
Lake Tanganyika	12,700	4,700	2,500
Lake Erie	9,940	210	573
Lake Winnipeg	8,555	70	710
Lake Ontario	7,540	738	247
Lake Titicaca	3,200	1,000	12,500
Dead Sea	360	1,300	-1,268
Crater Lake	25	2,000	6,239

THE ORIGIN OF LAKE BASINS

Basins resulting from crustal movements. The depressions which some lakes occupy have originated in diastrophic movements of one kind or another. A basin may be formed directly by a down-warping of the crust, or it may result from an uplift athwart a stream, which ponds the water and thereby forms a lake. The basin of Lake Superior was formed in part by a warping movement of the bedrock. In other instances the rock has fractured in several places, and large blocks have sunk along a number of cracks. Several of the deepest of the world's lakes occupy basins of this kind; among them are Tanganyika and Nyassa in Africa, and Baikal in Russia. Note also the diagram on page 260, which shows how fracturing has produced the basin in which the Dead Sea rests.

Basins formed by glacial action. Glaciers produce surface depressions through either erosion or deposition, or by a combination of the two. Hundreds of thousands of lakes exist in eastern Canada, north-eastern United States, and western Europe, a result of the glaciation which has within recent geologic times affected those regions. In mountainous regions lakes often occupy basins which were once the starting points of glaciers (see cirques, p. 182, and photographs on pages 182 and 183). Others are found in parts of glaciated valleys which have been dammed by the deposition of glacial drift. Lakes of this type frequently assume a rather characteristic aspect in relation to their environment (see Horseshoe Lake, Alaska, pictured on page 337). River valleys, even in plains regions, have been dammed up in the same way. Lakes in great numbers occupy depressions in broad moraines which have destroyed the previously existing drainage patterns. Lake Itasca (p. 136) is one of the thousands of glacial lakes of Minnesota.

Basins formed along stream courses. Streams may create several kinds of lake basins. Potholes, and especially the hollows excavated by young streams below waterfalls, may later become the beds of lakes. It is the older streams, however, which commonly leave depressions along their courses. Abandoned meanders often become oxbow lakes, and similar bayous may result from temporary channels established by



Minnesota Tourist Bureau

Most of the thousands of lakes in the northern states and in Canada owe their existence to the disruption of drainage by continental glaciers. Far-flung glacial moraines, spreading across the plains, have obstructed many river valleys, forcing the streams to find new courses. Scattered everywhere over this glaciated, low-lying country, lakes are forced to stand in local depressions in the morainic material while streams slowly re-establish their drainage patterns. On the left is shown Lake Itasca, source of the Mississippi River.

streams during floods. The low ground lying between a natural levee and the edge of the flood plain is often the site of small lakes; so is the equally poorly drained land between the distributaries of a delta. A heavily depositing stream may build its bed to such a height that the water of its tributaries cannot enter its channel; in this case the ponding of the tributaries may produce a lake at the mouth of each. Even the deposition of sediment in the form of an alluvial fan may dam up a stream sufficiently to form a lake.

Many obstructions in a stream's channel other than those due to the activity of the stream itself may cause the formation of a basin. Among these might be mentioned lava flows and mudflows, wind-blown sand, and landslides. Since landslides are especially likely to occur in the walls of canyons, lakes resulting from this cause are less uncommon than might be supposed. The illustration on page 51 shows a slide which dammed up the Gros Ventre River, Wyoming, producing a lake more than three miles long, while that on page 61 shows how Lake San Cristobal, Colorado, was formed by a mudflow.

Lake basins along seacoasts. Lakes occur rather commonly on coastal plains and along some ocean shores. Their presence is in some cases the result of the poor drainage generally prevalent in such areas, in others to the deposition of sand along the coast. Indentations in the

shore are cut off from the sea by these deposits, and bars are often built parallel with the shore, enclosing lagoons.

Basins resulting from other causes. Among the miscellaneous causes of lake basins might be mentioned those due to solution, such as limestone sinks, many of which are occupied by water. Occasionally also volcanic craters come to serve in the same capacity. Instances of this kind are found in Arizona, California, Oregon, and a number of other western states. The most notable example is Crater Lake in southwestern Oregon, shown on page 302 and on the map on page 438.

RELATIONS OF RIVERS AND LAKES

Rivers, it has been said, are the mortal enemies of lakes. With rare exceptions, lakes may be regarded as more or less temporary features of the topography. Rivers flowing into them bring in sediment, which is spread over the lake bottom. Rivers flowing out of them, on the other hand, cut down the outlets through which they pass, thus tending to drain off the water.

Thousands of limestone sinks dot the surface of the limestone area of central Florida. Most of these are occupied by small lakes.

Aero-Graphic Corporation



As a rule, filling contributes more to the extinction of a lake than draining, for an outflowing stream possesses practically no sand or gravel to serve as cutting tools. The water of the Lake of Geneva is said to require eleven years to flow from one end of the lake to the other, a distance of 45 miles. The velocity of currents in other lakes is presumably of a comparable order, and is much too slow to carry even the finest grit to the emerging streams.

Under special conditions, however, outflowing streams may degrade their lakes' outlets quite rapidly, as when they cut into poorly consolidated glacial drift, or loose landslide material. A striking example of the latter case is presented by the overflow of the dam created by the Gros Ventre landslide of 1925 (p. 51). When, some two years after the slide, water reached and overflowed the top of the dam, the swift current rapidly cut a channel 100 feet deep and 300 feet wide, resulting in a disastrous flood.

GEOLOGICAL WORK OF LAKES

The geological work performed by lakes corresponds quite closely to that effected by the ocean, although of course on a much smaller scale. Large lakes develop waves which actively erode their shores, although in smaller bodies of water the effects of wave erosion are negligible. In all lakes, however, erosive activities are confined to a very narrow vertical range. In this respect lake erosion differs from that of the ocean, which is carried on over a considerable range as a result of oceanic tides. Absence of tidal currents is another factor restricting erosion by lake waters.

Along the shores of lakes which freeze during the winter some erosion and transportation may be effected by expanding or drifting ice. Deep lakes in cold climates freeze around their borders, small ones generally over their entire surface. Water is densest at a temperature of about 39° F. Until this point is reached, water cooling at the surface sinks to the bottom and is replaced by warmer, less dense water from below. When a temperature of 39° is reached, however, convection ceases, the cold water remaining at the surface as the temperature continues to fall. Thus freezing occurs at the surface in lakes of moderate depth, while in deep bodies of water constant interchange between surface and bottom keeps the temperature from reaching 39°.

Lakes which are subject to severe freezing cause the formation of ridges which run parallel to the lake shores and are composed of unsorted stones, gravel, and sand. Freezing and thawing causes repeated thrusts of the ice upon the shore, piling up ramparts of loose debris.



United States Geological Survey, photograph by G. K. Gilbert

When lake water freezes it expands about nine per cent, exerting a strong lateral thrust upon the shores. If temperatures continue to fall, the ice contracts, resulting in the formation of cracks. These cracks fill with water, which may then freeze, causing another thrust upon the rocks of the shore. This process is shown in operation on a large scale on page 141. The result of these intermittent pressures is to pile up rock debris into walls or ramparts, several of which may border a lake shore. These ramparts are of unsorted materials, and their surfaces are inclined sharply toward the water.

Lake ice which is breaking up may be driven by winds upon the shore. Pebbles frozen in the ice blocks may thus be carried from place to place, and some erosive work may result from impact and abrasion.

In the deposition of mechanical sediments in lakes, the pattern is much the same as that of the sea. The coarsest sediments are deposited near the shore, and the others are laid in the order of increasing fineness away from it. The simplicity of this arrangement is modified by the proportionately large quantities of delta deposits. Almost all rivers emptying into lake basins develop deltas, which resemble those of the ocean in structure.

Lake deposits frequently include organic and chemical materials of a distinctive character. Masses of vegetation may accumulate, to be converted into peat, and perhaps later into coal. Lakes lack coral-reef deposits of limestone, as well as certain other types of oceanic limestone deposits; however, a soft, chalky mass of calcium carbonate known as *marl* may be laid down as a result of the accumulation of small shells or of the removal of carbon dioxide from the water by growing vegetation, or possibly of evaporation. It is found chiefly in small lakes. *Tufa* is a spongy or banded form of calcium carbonate, the mode of formation of which is probably similar to that of marl.

Microscopic one-celled plants known as diatoms remove silica from some lake waters and build it into beautiful glassy shells, which sometimes accumulate in beds of considerable thickness. The *diatomaceous earth* formed in this way is used as a polishing powder and in the making of certain refractories.

Iron oxide forms prominent deposits in some lakes. The origin of this material is partly organic, partly chemical, its presence being due to changes brought about both by bacteria and by chemical changes induced by the air. Iron oxide from this source is used as an ore in parts of Canada and Switzerland.

Many kinds of salts are deposited in certain lakes as a result of evaporation. These will be considered in connection with salines.

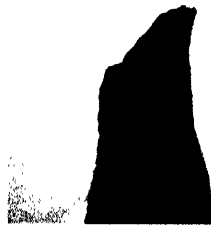
CHARACTERISTICS OF LAKE DEPOSITS

Sediments formed in lakes are in general well sorted, and are organized into beds of rather uniform thickness. Clastic sediments consist of fine, widespread clays, fine and coarse sands, and sometimes gravels. Lake waves and currents are not sufficiently strong to carry the coarser materials very far from shore, and there is therefore a rather rapid gradation in the texture of deposits from the shore outward. Extremely fine particles, however, remain suspended for long periods in fresh water; such particles may consequently be found in all parts of lake deposits, including those laid in the deepest water.

As a lake basin becomes shallower and smaller in area from the continued deposition of material within it, the heavier particles which are always dropped near shore are carried farther toward the lake's center as the shoreline shrinks. Lake sediments therefore present a typically coarser aspect nearest their margins, their materials becoming progressively finer in inward and downward directions. Other identifying characteristics are the presence of delta deposits, which are to be found at the mouths of all inflowing streams, and the presence of ripple marks and mud cracks.

Lake deposits may have certain special characteristics, both as to shape and constitution, determined by the nature of the lake in which they were laid. Glacial lakes tend to be somewhat circular in outline if they occupy cirque basins, elongate if caused by the deepening of sections of river channels, and irregular if produced by the regional

The expansion of freezing water, filling cracks in large bodies of ice, is of such great strength that it can cause the continental movement of an entire ice sheet! Let us see how this happens. Ice forms on the surface of the water because of water's low density when near the freezing point. A further fall or rise of temperature causes a contraction of the ice and often the formation of cracks or even huge crevasses. As the water which fills these cracks or crevasses begins to freeze, it exerts a tremendous lateral thrust on the surrounding ice.



United States Navy Photograph

disruption of drainage. Most deposits made in lakes of these kinds are thin and of small area; they often grade into swamp or bog deposits near the top, partly because of the small size of the depression in which they were laid, partly because the cool climate of their environment retards the bacterial destruction of vegetable matter.

Deposits made in oxbow lakes can be identified by their sinuous shape and alluvial character. They generally consist of rather well-laminated layers of mud and sand intermixed with organic materials and containing fossils of fresh-water organisms, surrounded by flood-plain deposits. These characteristics also apply to the deposits of other flood-plain lakes such as those confined between natural levees and the valley sides, except that the latter are of less regular shapes.

Lakes occupying hollows between the distributaries of deltas are also the sites of limited deposition. Deposits formed under these conditions are thin and comparatively small, consisting of muds and fine sands; occasionally they show evidence of inundation by the sea, sometimes containing marine fossils.

PLAYA LAKES

Many lakes in regions of rapid evaporation and restricted rainfall do not receive or retain enough water to maintain an outlet to the sea. Some evaporate altogether during the drier parts of the year. Such are the *playa lakes* of Nevada, California, Utah, and other Western states. Most playa lakes are small, but that occupying parts of the Black Rock Desert of western Nevada sometimes spreads out to a length of fifty miles, covering an area of as much as 500 square miles. Water covers the bottoms of playa basins to depths of a few inches, or at most a few feet, following heavy rains; at these times mud is brought into the basins and is washed from the margins toward the center. During the drier or warmer seasons the thin sheet of water disappears, frequently exposing a flat expanse of silt or clay, sometimes encrusted with salts; the dry lake bed is known as a *playa* (see photograph, p. 143).

SALINES

Also characteristic of many dry regions is the presence of *salines*, which may be defined as lakes containing a noticeable quantity of dissolved matter. The designation *salt lake* is usually restricted to salines in which common salt is the principal constituent, and *alkali lake* to those containing large amounts of the strong alkaline salts of sodium and potassium.

The substances most commonly present in saline waters are common salt, gypsum, calcium carbonate, and iron compounds; less frequently present in important quantities are sodium sulfate, carbonates of sodium or potassium, and borax. As the water of a saline evaporates, crystals of some of the substances present are deposited. This deposition is an orderly process, because each of the dissolved salts has its own limit of solubility.

The order in which different salts are laid down by a salt lake will depend upon the solubilities of the substances present, the concentrations of each, temperatures of the water, degrees of hydrostatic pressure, and perhaps other factors. In a typical case, calcium carbonate and compounds of iron are the first to be laid down; gypsum, somewhat more soluble than calcium carbonate but insoluble in strong salt water, is deposited next; finally, common salt separates out when its



United States Geological Survey, photograph by Piper

Harney Lake playa, Oregon. The broad, flat basin floor is covered by shallow water following rains.

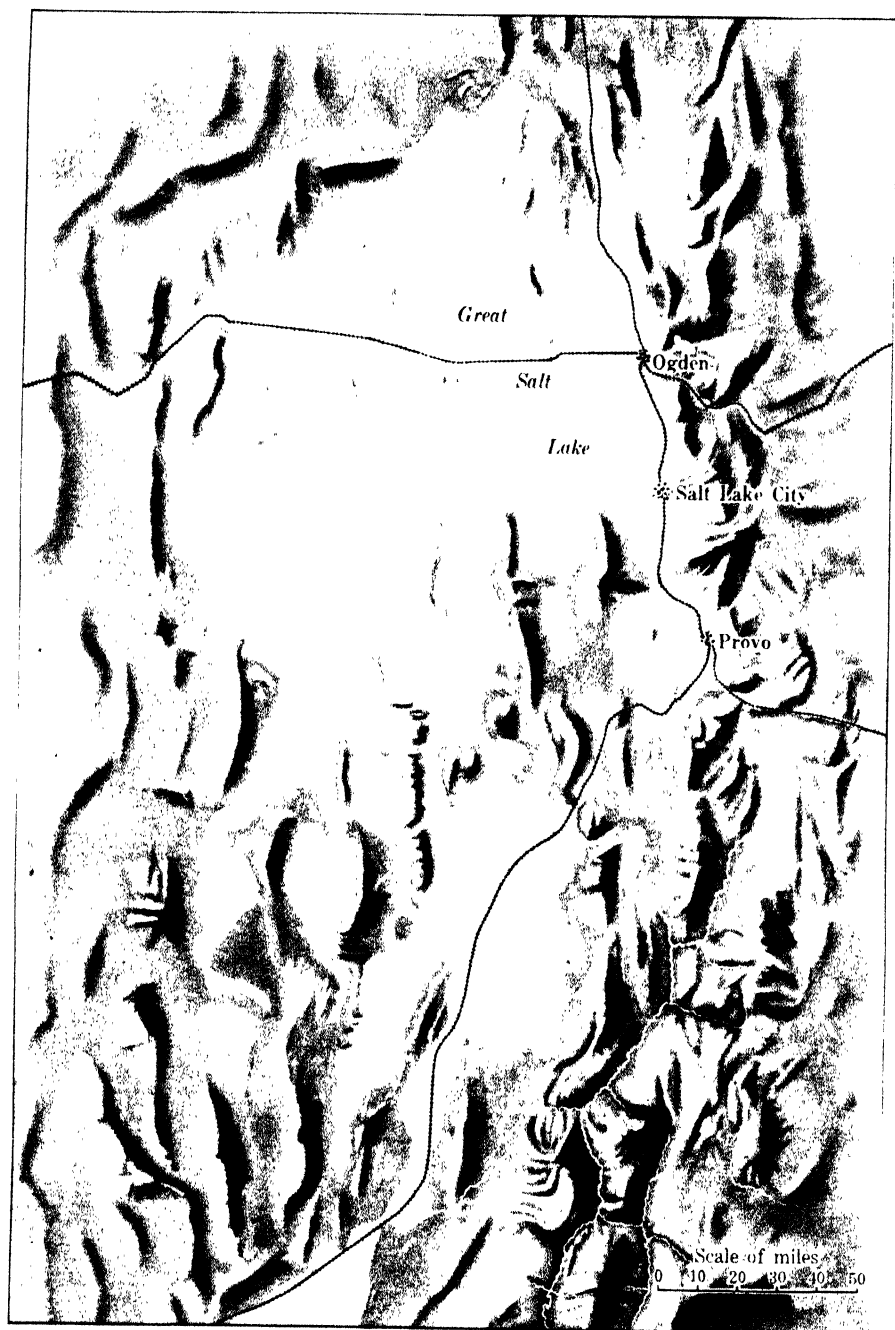
concentration reaches a point in excess of 30 per cent. Other compounds, such as salts of potassium and magnesium, remain in solution almost as long as water remains in the lake. Certain substances are much more soluble in warm than in cold water. These, of which Glauber's salt (sodium sulfate) is an example, may be deposited in winter and redissolved in summer.

When a salt lake dries up, commercially valuable deposits of salts may be left. Desert basins such as Death Valley sometimes contain important deposits of salt, borax, soda, or saltpeter.

The mechanical deposits of salt lakes resemble those of fresh-water lakes, except that, since sediments settle more quickly in salt than in fresh waters, the finer materials are dropped nearer shore. Organic deposits are practically absent.

Because of the lack of the regulating effect of outflowing streams, salt lakes are generally subject to considerable fluctuations of volume. For this reason, their deposits may be spread thinly over a comparatively large area surrounding that of the main site of deposition.

The largest lake in the world, the Caspian Sea, is a salt lake. Its surface is 85 feet below sea level. It was formerly connected with the Black Sea and through it with the Mediterranean, but has since been



Ancient Lake Bonneville, the ancestor of Great Salt Lake.

the sea receives from the Jordan River quantities of salt which have no escape to the ocean. The water surface is about 1300 feet below sea level. Its content of salt is extremely high—about 25 per cent.

Numerous salines exist in the Great Basin of the United States, the largest being Great Salt Lake in northwestern Utah. Although high above sea level, the waters of this lake have no outlet to the sea. The climate of the region is arid, the annual rainfall varying from 3 to 12 inches. The lake is but a few feet in depth, and has an area somewhat in excess of 2000 square miles. Its salt content varies from 15 per cent to almost twice that percentage.

The Salton Sea of southeastern California occupies a basin the bottom of which is 273 feet below sea level. The water of the Gulf of California is kept out of this basin by the large delta built at the head of the gulf by the Colorado River. A number of alkaline lakes occur in the western portion of the Great Basin.

EXTINCT LAKES

During the Ice Age climatic conditions in the Great Basin were very different from those of the present time. Lower temperatures retarded evaporation, and rainfall was much heavier. A vastly greater amount of water existed in the Basin than at present. A great lake, 20,000 square miles in area and more than 1000 feet deep, lay upon the present site of Great Salt Lake and extended beyond its boundaries, chiefly to the south and west. The water of this lake found an outlet at the north end of its basin, spilling over the mountains into the Snake and Columbia rivers.

This fresh-water lake, almost the size of Lake Michigan, has been named Lake Bonneville. It has left its record on the sides of the surrounding mountains in the forms of wave-cut terraces which can be traced for hundreds of miles, beaches, deltas, spits, and bars. As the climate became less humid and evaporation increased, the waters of Lake Bonneville fell below their outlet, and salt began to accumulate. In the course of its shrinkage the surface of the lake stood at several different levels, now indicated by terraces and cliffs. The shrunken remnant of Lake Bonneville is Great Salt Lake, one tenth the area of its immense ancestor; the abandoned lake bottom is the present site of Salt Lake Desert.



Standard Oil Co. (N.J.) , photograph by Roskam

Cypress swamp in Louisiana.

Another large ice-age lake of the Great Basin was Lake Lahontan in western Nevada, a district now occupied by Pyramid Lake and a number of other small salines. Unlike Lake Bonneville, Lake Lahontan never had an outlet, hence was salty from its beginning. It is notable for its vast deposits of a form of limestone known as travertine, which in places attain a thickness of 80 feet.

Lake Agassiz was another lake of glacial times, caused, apparently, by the presence of a great ice sheet to the north, which prevented the escape of the water into Hudson Bay. This enormous lake, larger than all of the Great Lakes combined, covered at one time or another 110,000 square miles in Manitoba, the northwestern part of Minnesota, and the eastern part of North Dakota. Melting of the ice destroyed the lake by opening a drainage way to the north, although shriveled remnants such as Lake Winnipeg remain. The ancient lake bed is almost flat, the soil is deep and rich, and the region is admirably adapted to wheat-growing.

SWAMPS AND BOGS

The term *swamp*, often used interchangeably with *marsh*, signifies a tract of soft, wet ground, sometimes covered to a slight depth with water; a *bog* is a morass of similar character which contains a considerable amount of vegetable material.

Swamps and bogs probably cover 1,000,000 square miles of the earth's surface, including about 100,000 square miles within the United States. They result from any of the conditions which produce poor drainage. Regions of very slight surface slope, such as coastal plains, abandoned lake basins, and land back of levees along rivers, are probable sites for the occurrence of swamps. Persistent dampness of the ground occurs most commonly, of course, in those parts of the world in which cool, moist climates prevail. In recently glaciated regions normal drainage has been disrupted in many places. Because of cool climates and imperfect drainage, swamps and bogs are very numerous in Canada and the northeastern states, and in northern Europe. Bogs are said to cover one tenth of the surface of Ireland. In warmer regions heavy rainfall, rank vegetation which retards runoff, and flatness of the surface may combine to produce very extensive swamps (see pages 147 and 149, on which the general aspects of



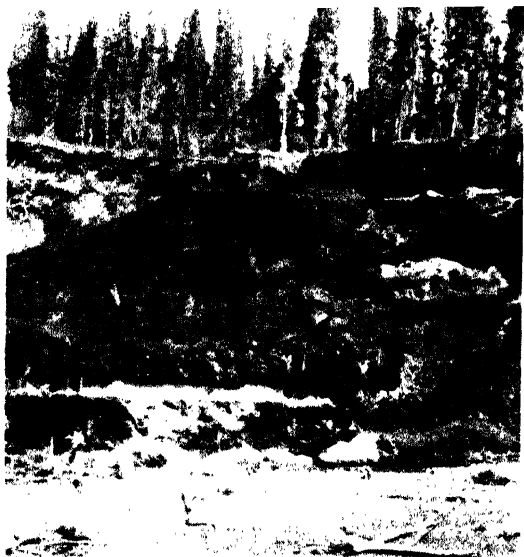
Florida News and Photo Service

*The Everglades, Florida. This great coastal plain swamp covers
5000 square miles.*

this type of swamp are depicted). Among examples of swamps in nonglaciaded areas are the Everglades of southern Florida and Dismal Swamp of Virginia and North Carolina, both coastal-plain swamps; many others exist in the tropics and subtropics.

All kinds of moisture-loving plants are to be found in swamps, among them sedges, rushes, ferns, mosses, and grasses. In temperate climates the sphagnum moss is prominent in these situations; its spongelike capacity for holding water may permit it to grow for some distance beyond the source of the water, thus extending the area of the swamp. Cypress trees also grow in standing water, while mangrove thickets flourish in some salt swamps along the seacoast.

The most characteristic feature of swamp or bog deposits is a large, perhaps a predominant, proportion of organic matter. In flood-plain swamps this is mixed with much inorganic material, giving rise to a black muck. In ponds and lakes of glacial origin and in some other types of situations, vegetable matter may accumulate far more rapidly than mechanical sediments, living plants growing at the surface upon gradually thickening masses of dead plant material. The vegetable matter is protected from decay through the exclusion of the air by the water in which it accumulates. Chemical decomposition ensues, the more volatile constituents being lost, while the carbonaceous content becomes more and more concentrated. This process results in the conversion of the plant material into the light, spongy, brownish substance known as *peat*. A deposit of peat is shown in the illustration on page 150. Coal is the product of a more advanced stage of this



United States Geological Survey, photograph by F. H. Moffitt

A dark, thick deposit of peat, interbedded with light-colored volcanic ash, testifies to the bog conditions which existed here in the past. Its recent formation and the lack of high pressures have held chemical decomposition in check, but the peat is still hard enough to resist erosion. In time this peat would have become lignite, bituminous ("soft") coal, and finally anthracite ("hard") coal.

process, and the coal deposits of the present day mark the locations of great swamps of the past, some of which may be seen on page 396.

Thin beds of iron compounds and of other minerals also occur in some bogs.

VIII · THE ATMOSPHERE



Although constituting less than one one-millionth of the mass of the earth, the atmosphere exerts a profoundly important effect upon the earth at its surface. Without air there would of course be no life, except perhaps of the most primitive sort. There could be no sound, no odor. Fire would not burn, metals would not rust. There would be no gradual dawn or twilight, for these phenomena result from the refraction of light by the atmosphere. The sun would rise without warning and beat down fiercely upon the unprotected earth, sending terrestrial temperatures far above those which are ever normally experienced; it would set just as suddenly, and the earth would then cool rapidly to temperatures far below the zero mark. Without an atmosphere there would be no blue sky, and the stars would shine all day long against a perfectly black background. There would be no storms, no rain, no change to enliven the landscape except the unheralded crash of meteorites against the rocks.

THE ATMOSPHERE AS A PART OF THE EARTH

Constitution of the atmosphere. The air, one of the four "elements" of the early Greeks, was not differentiated into its separate parts (except with regard to water vapor) until the latter part of the eighteenth century. In 1752 carbon dioxide was isolated, and twenty years later nitrogen and oxygen were also identified. It was not until just before the beginning of the present century that the presence of the rarer atmospheric gases was demonstrated.

Analysis of dry air reveals the following composition:

Gas	Percentage by Volume	Gas	Percentage by Volume	Gas	Percentage by Volume
Nitrogen	78.03	Carbon dioxide	.03	Helium	.0004
Oxygen	20.99	Hydrogen	.01	Krypton	.000005
Argon	.93	Neon	.0012	Xenon	.0000005

In addition, the atmosphere always contains variable quantities of water vapor and of impurities such as dust, pollen, microorganisms, and smoke particles. Solid impurities are more abundant over land than above the sea, and usually more so in the vicinity of cities than in country districts. Water vapor constitutes from a fraction of 1 per cent up to as much as 5 per cent of the atmosphere, depending upon the locality and the weather conditions; its total quantity the world over is sufficient to provide a one-inch rain over the entire earth.

Slight variations in the composition of the air occur with changes in latitude. There are also changes with variations in altitude, but these do not appear to be as great as would be expected from the differences in densities of the constituent gases. Proportions of the permanent constituents are essentially unchanged in the lower several miles of air, and spectroscopic analyses of the aurora borealis reveal the presence of both oxygen and nitrogen at great heights, while the natural expectation of finding hydrogen and helium in the upper atmosphere has not been realized. Ozone, a form of oxygen which occurs only as traces in the lower atmosphere, is much more plentiful at high altitudes.

Pressure, density, and height of the atmosphere. The fact that the air exerts pressure was not known before the time of Galileo and Torricelli, the latter of whom invented the mercurial barometer in 1643. Eleven years after this important event Guericke gave his famous demonstration that sixteen horses could not tear apart the two halves of a hollow sphere from which the air had been removed.

Torricelli's barometer was essentially like the modern instrument, which consists of a tube of mercury closed at one end and inverted in a vessel of the same liquid. The mercury in the tube stands at a height which is governed by the weight of the air pressing down upon the surface of the mercury in the vessel at the base of the instrument; the weight of the mercury in the tube is just equal to the weight of a similar column of air, extending from the surface of the mercury in the vessel upward to the highest limits of the atmosphere. Normally the air at sea level supports 76 centimeters, or nearly 30 inches, of mercury. To express it another way, the air at sea level exerts a *standard* pressure amounting to 14.7 pounds per square inch of surface.

Since the air supported by one square inch has a weight of 14.7 pounds, the entire mass of the atmosphere can be calculated by multiplying this figure by the number of square inches of the earth's surface. The result is approximately 5.9×10^{15} tons, or 5,900,000,000,000,000 tons.¹

This quantity of air, *at uniform sea-level density*, would make a blanket five miles thick over the earth. But the density of the air is far from uniform; air is highly compressible, and is therefore of maximum density next to the earth, becoming progressively thinner with increasing altitude. One half of the atmosphere, by weight, lies within three and one-half miles of sea level, the other half being distributed in increasingly attenuated condition for many miles out into space. At an altitude of 72,395 feet, almost fourteen miles, the *Explorer II*, an army balloon, obtained a barometric reading of only .6 inch, indication that it had risen above fully 96 per cent of the entire atmosphere.

Over how much space is the remaining 4 per cent distributed? It is said that the Arabs of the eleventh century calculated the height of the atmosphere from the duration of twilight. The lingering of light after the setting of the sun is due to the refraction or bending of light rays around the earth by the atmosphere and its contained impurities. The height at which the air is dense enough to effect this refraction can be obtained from the trigonometric functions of an angle at the earth's center determined by the distance through which the earth turns between sunset and the time of the disappearance of the last vestiges of twilight. The method yields a value of 44 miles, which is in fair agreement with the results of the reputed Arabian calculations.

But the air is known to extend far above the level at which its density is sufficient for appreciable refraction of light to the earth. Meteors, which owe their incandescence to friction with the atmosphere, and to the heat generated from the compression of air in front of them, have been observed to glow at altitudes of around 200 miles. The aurora borealis, which is also an atmospheric phenomenon, is reported to have reached heights of more than 600 miles.

There is, however, a definite limit to the air which can be con-

¹Strictly speaking, allowance should be made for the elevation of land masses above sea level and for a number of other factors. The corrected figure is slightly smaller than the one given here. It should be pointed out also that the result obtained by use of this method represents the *weight* of the atmosphere, which is not exactly the same as its mass.

sidered to belong to the earth. While the density of the atmosphere doubtless decreases gradually until it is indistinguishable from that of interstellar space, the molecules participating in the earth's rotational movement are probably limited to a distance from the earth of about 20,000 miles, at which point centrifugal force may well be sufficient to offset the attraction of gravity.

Air temperature. The air receives very little heat directly from the sun. Solar radiation contains a large proportion of relatively short waves, such as those comprising the visible parts of the spectrum, which we know as light. To these the atmosphere is almost perfectly transparent. Altogether, some 15 per cent of the radiation falling upon this planet is absorbed by the air and 50 per cent by the rock and water of the earth, the rest being reflected back into space by the earth. The solid and liquid parts of the earth at length lose the energy they have absorbed. Some of this energy is transferred, in the form of heat, directly to the air by conduction. Some is lost by radiation as heat waves, to which the atmosphere is much more opaque than it is to light. Much of this radiated energy is trapped in the lower portions of the atmosphere which, largely because of their relatively high water-vapor content, have an especially strong heat-holding capacity. The

United States Weather Bureau



Full expression of the tremendous force that lurks in the movements of the atmosphere is reached only in the tornado. These terrible storms result from convection currents, formed by the confluence of masses of warm and cold air. Although the path of a tornado is usually narrow, it is often marked by tragic destruction. The upward, raging vortex of warm, moist air forms a great pillar of wind, dust, debris, and even parts of houses or trees moving at speeds as great as 400 miles an hour.

air, therefore, receives most of its heat from the earth. For this reason, air temperatures near the ground are usually higher than those at higher altitudes; a decrease of 1° Fahrenheit per 300 feet of increase in altitude may be taken as a general average. This drop in temperature continues upward for a number of miles. A difference in altitude affects the temperature about 800 times as much as an equal difference in latitude.

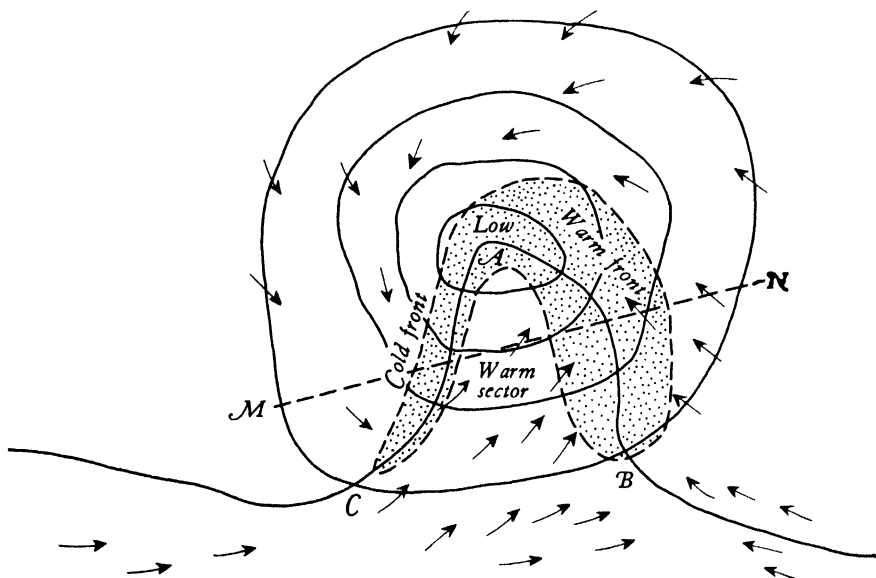
Movements of the atmosphere. The density and pressure of the air do not remain constant in the lower parts of the atmosphere, but vary in response to a number of conditions. Heating, by causing air to expand, reduces its density. The addition of water vapor has the same effect, because the water vapor is only about two thirds as heavy as dry air. Near the equator, these factors produce a zone of thin air, circling the earth. This thin air rises, because of the pressure of cooler air moving in from north and south. These cooler layers of air constitute the trade winds. Because of the rotation of the earth they are deflected—toward the west in the northern hemisphere, toward the east in the southern—giving the trades a southwesterly and a northwesterly direction respectively.

The air rising above the equatorial regions separates into two streams, moving northeast and southeast above the trade winds. These currents settle to the earth in latitudes of 30° or higher, creating areas of higher-than-average pressure in these regions.

Across the northern half of the United States this eastward-moving belt of air constitutes the prevailing westerlies. Within this belt large masses of air under low and high pressure, known as cyclones and anticyclones respectively, travel across the country at brief intervals, bringing with them changes in the weather. In the cyclone, air is moving in an upward spiral in a counterclockwise direction, its moisture frequently condensing into clouds. The heavier air of the anticyclone is moving downward in a great clockwise-turning spiral, usually producing clear, cool weather.

The causes of the formation of cyclones are not thoroughly understood. Formerly regarded merely as eddies in the prevailing westerlies originating in strong local convection currents, they are now generally thought of as being the results of the interaction of cold and warm masses of air flowing past each other in opposite directions. If a pro-

jecting portion of the warm, eastward-moving mass invades the region of the cold, westward-moving air, it becomes partially surrounded by cold, heavy air, and a "low" results. This situation is shown in the diagram on this page. From this diagram it may also be seen that the air participating in a cyclonic movement does not circle continuously around the vortex. The winds blowing into the warm sector, in fact, come from an entirely different region from those of the cold sector; their speed of rotation, furthermore, is often less than the for-



A well-developed low-pressure area. Region of condensation indicated by stippling. Wind direction indicated by arrows.¹

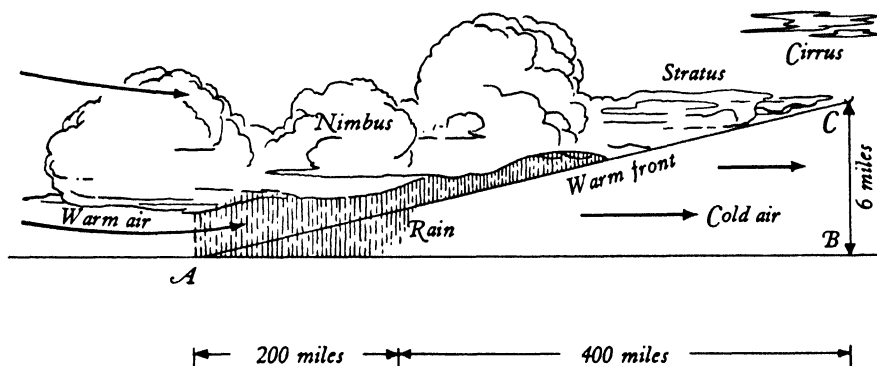
ward rate of movement of the cyclone, showing that they do not permanently accompany the disturbance on its journey across the continent.

As the cyclone advances, the air forming the foremost (east) edge of the warm sector is pushed upward over the cold air with which it comes in contact, forming a "warm front" (line AC in diagram on this page). The cooling of this displaced air causes the formation of clouds, and rain may fall, perhaps several days after the appearance of the first clouds. At the rear of the warm sector a "cold front" de-

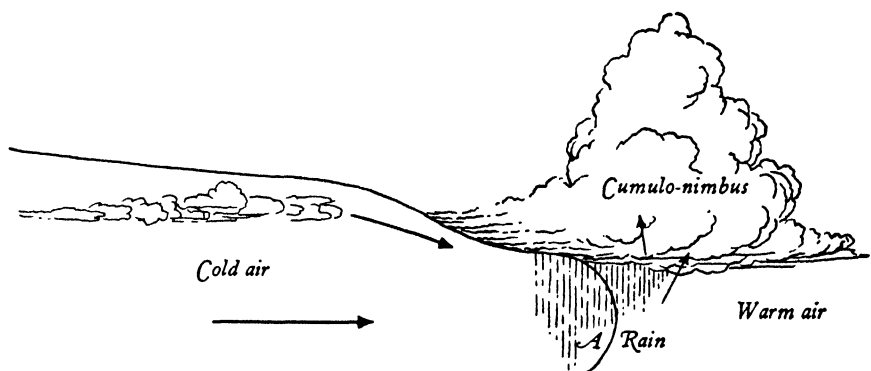
¹From *Physical Meteorology*, by John G. Albright. Copyright, 1939, Prentice-Hall, Inc.

velops; the cold air, moving roughly at right angles to that of the warm sector, forces its way under the warmer air of that region. Rain may occur here also, usually developing more suddenly than that which accompanies a warm front. The conditions within warm and cold fronts are shown in the diagrams on this page.

Layers of the atmosphere. This lower portion of the atmosphere, this region of clouds and storms and changeable winds, is known as

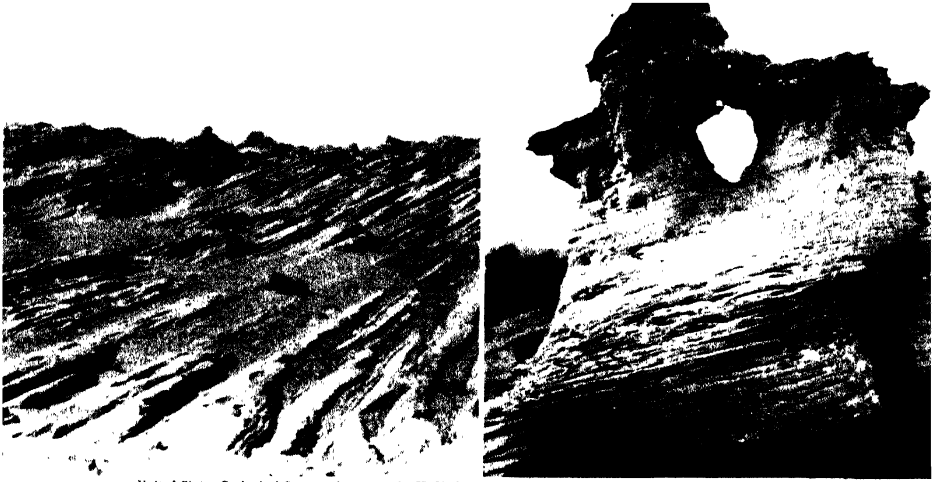


A vertical cross section through the warm front shown in the preceding diagram, taken along the line MN, the vertical scale being very much exaggerated. The distance AB is usually about 400 or 500 miles, while the elevation of C is usually 6 or 8 miles. The storm is advancing from left to right.¹



A cross section through the cold front shown in the diagram on page 156, along line MN. The vertical scale is greatly exaggerated. The storm is moving from left to right.¹

¹From *Physical Meteorology*, by John G. Albright. Copyright, 1939, Prentice-Hall, Inc.



United States Geological Survey, photograph by H. E. Gregory United States Geological Survey, photograph by Walcott

(Left) *Effects of wind erosion on inclined layers weakened by bedding planes.*
 (Right) *Wind-eroded sandstone. Teton County, Montana.*

the *troposphere*. Its upper limit, the *tropopause*, stands at an altitude of about eleven miles above the equator and slopes downward toward the poles, where it is four or five miles high. Temperatures of the tropopause are considered to range from about -112° F. in the equatorial region to -50° F. above the poles, although recent researches with rockets indicate greater extremes of temperature, as well as a greater altitude, for this region.

The steady decline in temperature with increased altitude ends abruptly at the tropopause; above it, strangely enough, temperatures appear to rise, until at an elevation of twenty-five or thirty miles they may approximate those of the earth's surface. This is the region known as the *stratosphere*; compared to the troposphere, it is a place of extraordinary calm. It contains almost no dust or water vapor, and such air movements as exist are steady in both force and direction. The sky is black, for the air is much too thin to diffract light rays in any quantity. The stratosphere extends upward to a distance believed to be in the neighborhood of fifty miles. At this height the temperature has again dropped, standing at about -150° .

One possible reason for the increase in temperature above the tropopause is the capacity of ozone, present in considerable quantity in the stratosphere, for absorbing radiation. The ozone layer, which under normal atmospheric pressure would have a thickness of only one eighth of an inch, occupies a region between fifteen and thirty miles in alti-

tude. It has a high capacity for the absorption of radiation beyond the violet end of the spectrum, and its density and thickness are just such as to permit the passage of the quantities of ultraviolet light necessary to a continuance of life on the earth, and yet sufficient to screen out lethal doses.

Above the stratosphere the immense *ionosphere* stretches upward. In this little-known region the aurora glows and melts away and reshapes itself. Here too are several zones of electrified gases, which were detected through their ability to reflect radio waves back to the earth. Temperatures again show an increase in the ionosphere, and are believed to reach 1000° at an elevation of 125 miles.

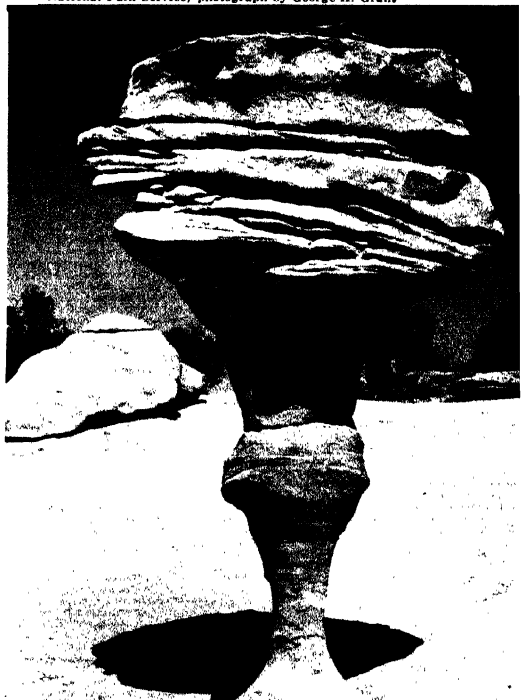
GEOLOGICAL WORK OF THE ATMOSPHERE

Erosion

The wind as an erosive agent. In regions of average humidity the wind, in comparison with water, is a very minor factor in the erosion of rocks. Because of its low density, it is unable to deliver consistently forcible blows against the lithosphere. Even so weak a binder as moisture is sufficient to hold loose soil particles together in most instances, while the roots of plants are very effective in this particular. An

An odd erosional remnant in southeastern Utah. This monument stone, known as "Venus' Goblet," is the wonderfully balanced product of wind erosion and weathering. The goblet effect in this mass of bedded sandstone was produced by the varying resistance of the rock from top to bottom. The slender stem of the goblet must be firm, and relatively untouched by chemical weathering, to hold up such a weight of rock. Note the enlargement in the base of the structure and the deeply incised grooves at the top.

National Park Service, photograph by George A. Grant



abundance of vegetation serves as a protection to the surface of the ground and materially decreases the velocity of air currents striking it.

It is in the dry regions of the earth that the wind becomes an important, perhaps the dominating, agent of erosion. Aridity and sparseness of vegetation, usually coupled with exceptionally strong winds and an abundant supply of sand, supply the essential conditions for maximum development of the wind's geological work. In deserts and near deserts much work may be accomplished through the lifting power of winds alone, especially in their action on unconsolidated materials. Even rocks of considerable size may be moved about. This is particularly likely to be the case on mountain tops, for the force of the wind increases sharply with altitude; a velocity of 210 miles per hour has been recorded on the top of Mount Washington.

Most of the wind's erosive work, however, is accomplished through abrasion. Hard grains of quartz sand are picked up and hurled against projecting rocks. The lightness of the air is partly offset by its motility, and under the influence of the strong winds common to arid

Domain of the wind. Over that one-fifth of the earth's land surface in which neither moisture nor vegetation can offer substantial resistance, the atmosphere becomes a geological agent of great importance.

Bureau of Reclamation



regions this sand blast is directed against the bedrock with destructive effect. On the western plains panes of glass have become opaque under continued exposure to wind-blown sand; windshields have lost their transparency during a single storm. Foundations have been eaten into at the surface of the ground, and fence posts and telegraph poles have been cut down by impact of the sand. In one experiment a glass bottle was cut completely through in a period of two years. In view of these facts, it is hardly surprising that the wind, under especially favorable conditions, can become a powerful eroding agent.

One fifth of the land surface of the earth is said to be too dry for agricultural purposes, and this area may be taken roughly as that in which the erosive activity of the wind reaches a stage of major importance. Most of this arid region is included within the trade-wind belts or within the borders of high plateaus, or is located on the leeward sides of mountain groups. In the trade-wind belts, extending approximately 30° on each side of the equator, the winds become warmer upon approaching the equator, and therefore drier, since rising temperature increases the capacity of the air for taking up moisture. In plateau or "rain-shadow" situations most of the moisture originally present in the air is lost in ascent of the slopes.

The wind is not without significance as a geological agent even in some sections of regions that are well watered. Along ocean and lake shores large surpluses of sand may accumulate. Because of the coarse character of the sand grains, water drains rapidly out of such accumulations, while capillary water has little tendency to invade them from below. They therefore often dry out quickly and remain dry much of the time, permitting effective wind work upon them. The effects of wind action are also often noticeable along the shores of sandy rivers.

Characteristic effects of wind erosion. Desert sand grains exhibit characteristic effects of impact by other sand grains. Whereas the water of river or ocean acts as a cushion between the grains to temper the force of their mutual blows, sands of the desert have no such protection, and their grains are blown against each other with telling effect. These grains show the rounding effects of abrasion in more pronounced degree than do those of most streams, and in addition their surfaces are frequently chipped, cracked, or pitted, and may exhibit the translucent appearance of ground glass.

A larger fragment such as a pebble, long subjected to the impact

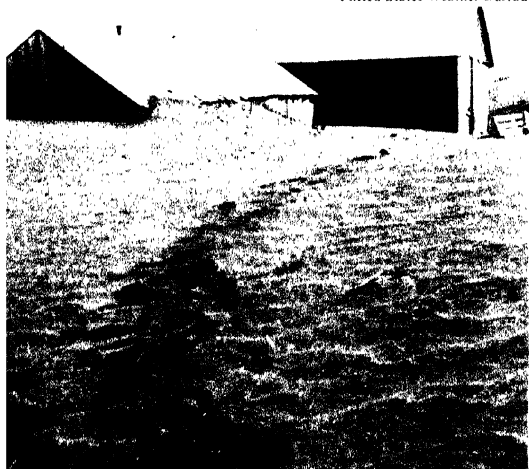
of wind-blown sand, will be worn away chiefly on the side turned toward the prevailing wind. If abrasion continues long enough, the exposed side will be smoothed off and polished, appearing usually as a slightly convex surface. If then the pebble is undermined and rolls into a depression, another face may be exposed to the wind, to be ground down in a similar manner. In this way the curious wind-carved stones known as *ventifacts* are produced. (See the illustration on page 191.) In typical instances these objects appear with two or three smooth facets which meet along well-defined ridges. There is little or no tendency toward spherical shape, and many of them are noticeably elongate.

Some very fine ventifact specimens have been formed in the beds of canyons, where the winds passing over them can blow from only two directions.

Wind erosion plays a part, although a minor one, in the general reduction of the lithosphere. In favorable situations it also helps to produce somewhat spectacular topographic forms (see page 159). This is especially true in regions in which rocks are of differing hardness, in which case they may become pitted or otherwise marked by the effects of differential erosion. Some natural bridges have resulted largely from the action of wind-borne sand.

In arid and semiarid regions, basins a few inches to many feet in depth may be excavated by the wind, especially during drought years or following the removal of vegetation. In deserts such basins may become very extensive. Unlike water, wind is able to reduce the region it is eroding to a level below that of the sea; its action is restricted, however, by the presence of ground water, and basins resulting from wind action cannot extend below the water table.

United States Weather Bureau



A tragic but not uncommon result of wind transport in the "dust bowl" area of western Texas, Oklahoma, Kansas, and southeastern Colorado during the early 1930's. High wheat prices stimulated the plowing of extensive grassland areas, bringing profits as long as normal rains continued, but disaster when they failed.

Transportation

The load of the atmosphere. The atmosphere acquires its load from many diverse sources. Most abundant is fine earthy matter picked up from plowed fields, city streets, and dry land everywhere. Intermingled with it are particles of smoke, pollen, spores, and microorganisms. Volcanic explosions pour quantities of dust into the air, some of which may be carried about by air currents for years. Winds sweeping dry beaches, flood plains, or the beds of dry lakes find dust and sand to be moved, usually weathered feldspars and quartz, sometimes gypsum, salt, or other minerals, and in some cases grains from disintegrated sea shells.

The air as an agent of transportation. As compared with water, the transporting power of the wind is not great. Under average conditions, its effect in the movement of sand grains or particles of larger size is relatively unimportant, although dust is abundant in the atmosphere, and may be raised from a dry surface by the faintest breath of air. Traveling dust motes can be noted in a beam of light crossing a darkened room. The same observation can be made on a larger scale in the phenomenon known as the sunburst, which is caused by the scattering of light rays by dispersed dust in the path of sunlight through a rift in an overcast sky. Dust may often be seen rising in small whirls above hot ground, and great columns of dust are often observed moving majestically across desert or dry plain. Dust from volcanic explosions has been traced entirely around the earth, and has been known in some instances to remain in the air in detectable quantity for several years.

In regions of ordinary rainfall, surface mantle is kept more or less damp, and the water table generally remains sufficiently high to supply water which causes adherence of weathered particles. Where there is abundant rainfall, also, there is almost always abundant vegetation, the roots of which bind mineral grains against the dispersive action of the wind. Even dust blown in from outside regions does not remain for long in the atmosphere of a humid area, for frequent rains soon wash it down to earth.

But in the arid and semiarid parts of the world transportation by wind, like erosion by the same agent, becomes an important geological

process. The weakness of the air's lifting power (as compared with that of water) is compensated for to a large extent by its great volume and by the velocity which it often attains. In Nebraska great damage was brought about by "blowouts" which started in overgrazed portions of fertile grasslands (see illustration, p. 165). During the droughts of 1934 and 1935, spring winds caught up fine soil from the Dust Bowl area of the high plains in such quantities as to bring disaster to the sections affected. Dust storms darkened the sky, reducing visibility to a few feet. Fences were buried, and drifts piled high against the sides of houses and barns. These "black blizzards" ravaged the rich farm lands which gave them birth, and dropped the finer substance as far away as the Atlantic seaboard.

The carrying power of the air, like that of water, depends upon its velocity, but in this case also the relation cannot be expressed in any simple mathematical formula. Moving at 5 miles per hour, air can support material comparable to silt carried by a river, while a velocity of around 30 miles per hour is necessary for the effective transportation of sand. Since the ratio of the surface area to the volume of an object varies inversely with the diameter, it is only the very finest material that remains suspended for long at a time.

A factor which magnifies the comparative efficiency of the atmosphere as a transporting agent is its great volume. According to Udden, one cubic foot of air moving at the rate of 5 miles an hour can support .0015 grams of finely pulverized material. From this value it is estimated that the transporting capacity of winds blowing across the Mississippi basin would have 1000 times the transporting power of the river itself. Dust storms, further, are sometimes borne on winds traveling 30, 40, or even 50 miles per hour—perhaps ten times the speed of the water.

In deserts and other regions which are plentifully supplied with sand there is usually considerable movement of this material along the ground. One third of Arabia and one ninth of the Sahara are covered by sand, much of which is constantly being shifted about. Along ocean shores and on the leeward sides of many lakes and rivers sand is driven landward by the winds until it mingles with the moist earth or is stopped by the growth of vegetation. Often this wandering sand is concentrated into masses called *dunes*. Sand is driven up the windward slopes of these structures, and dropped on the protected



Soil Conservation Service

Millions of tons of dust and sand may be transported during a single storm.

Overgrazed grasslands of Nebraska suffered severe damage from wind erosion.

United States Forest Service



sides. Dunes migrate at rates varying from zero to more than 100 feet per year. Much migrating sand, however, is not organized into dunes, but moves as a sheet near the ground. Sandstorms featured by mass movements of this kind are characteristic of the sandier types of deserts.

Migrating sand has done much damage. In the southwestern United States, in France, and elsewhere creeping dunes have buried farm lands, roads, railroads, forests, and even villages, while in Africa and central Asia many ancient cities have been overwhelmed by the ceaseless flow of sand.

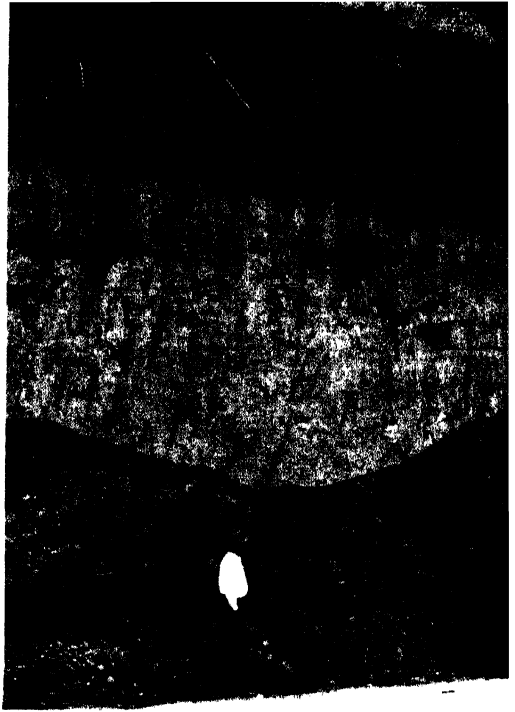
Of the various agents of transportation and distribution, wind is at once the most versatile and the most cosmopolitan. Unlike rivers and glaciers, the wind is free to move materials over the earth's surface in any direction. Also unique is its ability to pluck material out of entirely enclosed basins, from which no other agent has the power to remove them. Through its action, particles can be picked up and carried to levels higher than the surfaces upon which they originally rested. It has been suggested that every square mile of the land surface of the globe contains contributions from every other square mile, brought to it chiefly through the action of the wind. While this statement should not be accepted too literally, there is no question that dust is spread by this agency for many thousands of miles from its point of origin.

Deposition

Characteristics of atmospheric deposits. Sediments dropped from the air are as a rule more thoroughly sorted than those laid down by water. In structure, however, wind deposits are often much less regular than those of marine or even fresh-water origin; cross-bedding of a pronounced character is a common feature of many aeolian (wind-laid) accumulations, particularly those which have resulted from transportation along the ground. Well-formed ripple marks are also common in atmospheric deposits, though they are seldom permanent.

Dust deposits. In spite of the large total amount of fine dust present in the atmosphere, the rate of deposition of this material is in all ordinary cases extremely slow. It has been estimated that the dust which has fallen upon the continent of Europe during the past 2000 years would have an average thickness of five and one-half inches; this

Loess bluffs near Omaha, Nebraska, showing the characteristic tendency of this material to stand in vertical cliffs. The material composing such deposits is more finely grained than sand. Instead of being formed of water-rounded particles which would slide over one another, allowing the whole mass to slump, loess deposits are formed of mechanically ground, chemically unweathered fragments whose sharp corners serve to bind the whole mass together. The vertical position of the roots shown in the illustration suggests the reason for the columnar cleavage usually found in loess deposits.



G. E. Condra

indicates an annual rate of only about $1/400$ of an inch. Dust which accumulates so slowly is worked over by organisms and other natural agencies until it becomes integrated with the soil, leaving no distinctive deposit.

Under special circumstances, dust deposits accumulate in appreciable volume. During heavy dust storms the effects of settling dust may be noticed many miles from the source of the material.

Volcanic explosions provide one of the important causes of the deposition of dust. Volcanic dust, generally considered as an igneous rock, may just as accurately be regarded as sedimentary, since it settles out of the atmosphere. Volcanic dust may cover extensive areas as thin sheets, so persistent that they may be used as valuable key horizons for the identification of associated formations. Dust from volcanoes may also accumulate as localized drifts of considerable size.

Loess. In a number of parts of the world, thick accumulations of a yellowish-brown material, intermediate in texture between that of sand and of clay, form conspicuous and important deposits. This material is known as *loess*, and it is regarded as being in the main aeolian sedi-



National Park Service, photograph by George A. Grant

*Sand dunes of pure gypsum in the White Sands National Monument,
New Mexico.*

ment, although some of it appears to have been partly of glacial origin. Loess consists of claylike particles containing angular, little-weathered grains of quartz, feldspar, mica, and other common minerals. Its deposits are unstratified, unless modified by the action of water. One of its striking characteristics is its ability, in spite of its loose, crumbly nature, to stand in steep, straight cliffs; this property is due to the sharpness and angularity of its particles, which resist tendency to slipping, and also to the presence in it of many small vertical tubules, probably the openings left by the roots of many generations of plants, which give the material a sort of vertical cleavage.

The largest deposits of loess are situated in northern China, where the material has accumulated to depths of hundreds of feet. It has been transported from the deserts of central Asia, being composed of the softer and finer particles which the wind is able to pick up and remove from among the heavier products of rock disintegration. Having been but little exposed to the solvent action of water, it makes a soil of unexcelled fertility, and has in this region supported a vast population of Chinese for many centuries. Thousands living in the loess district make their homes in caves excavated in the soft walls of the cliffs. The Yellow River and the Yellow Sea have received their names from the heavy load of loess which they carry. In northern Argentina another deposit of loess has accumulated, the result of deflation from deserts to the west. Along the Rhine, the Missouri, and the

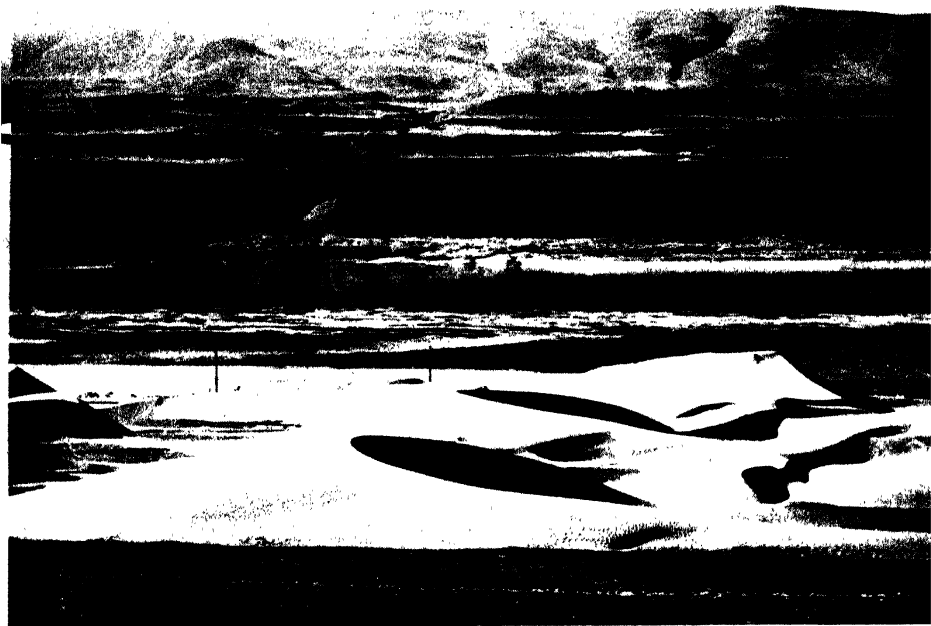
Mississippi rivers other deposits occur; in the formation of these, however, the wind has played only a secondary part, spreading the material across the "corn belt" and adjoining regions after deposition had been effected by other agencies.

Aeolian sand deposits. Disintegration of rock in desert regions is followed by a sorting and separation of the resulting particles, brought about by the action of the wind. Softer materials are ground to such fineness that they can be deflated, traveling on the wind until they reach a more humid district, perhaps forming a deposit of loess. More resistant materials form great expanses of sand, lying against mountain slopes or stretching endlessly away across the plain. The sand drifts with the winds, usually in the form of dunes, while rock fragments too large to be moved about remain as *lag gravels* until reduced to a size such that they can be transported by the wind.

Dune sands usually contain a high proportion of well-rounded grains of quartz. Under some circumstances, however, other kinds of sand accumulate in quantity and are heaped into dunes. Examples of these exceptional cases are the calcite dunes of Bermuda, which consist of sand derived from coral limestone, and the "white sands" of southern New Mexico, which are of nearly pure gypsum.

In districts of very strong winds, dunes may be elongated in the direction of the wind, but under most conditions they lie at right angles to it. If the supply of sand is moderate, sand is often blown around the ends as well as over the tops of the dunes, resulting in a crescent-shaped mass, the horns of the crescent pointing away from the direction of the prevailing wind; dunes of this shape are known as *barkhans*. In regions of frequently changing winds, sand dunes are irregular mounds, of no specific shape.

The inclination of the windward side of a dune is low, perhaps in the neighborhood of 10° to the horizontal. The forward side is much steeper, in some cases reaching an inclination of 30° or more. Because of the nature of dune movement and of the changeableness of the wind, dune sands are strikingly cross-bedded. Being exposed to the air in regions which in most cases have an arid climate, they are light in color—white, gray, yellow, or sometimes red—and contain few if any fossils. Their surfaces are often marked by conspicuous sand ripples, as may be seen in the illustration on page 170.



United States Geological Survey, photograph by Gilbert

Barkhans. Near Biggs, Oregon.

Ripple marks made by the wind are common, but seldom endure.

National Park Service, photograph by George A. Grant



Dunes range in size from small mounds to masses of almost mountainous height. Dunes of the Sahara are reported to be 600 feet high, while still larger ones are to be found in especially favorable locations. Their length may be one-half mile or more, although this is unusual.

Dunes of course reach their best development in desert regions. Arabia is probably the sandiest region of comparable size on the earth, and it has many well-developed dunes, which are confined to about one third of its area. The Sahara, proportionately less sandy than the Arabian desert, also has many dunes of great size. Dunes also exist in abundance along the shores of some lakes and seas. Although such locations are rarely to be described as arid, sand washed up by the water dries out quickly. Along much of the Atlantic coast of the United States and of the eastern shore of Lake Michigan dunes form conspicuous features. They line the banks of many rivers. In some sections of the West and Central West they occur over large areas. Among the largest dunes in the world are some located near Alamosa, Colorado, where they occupy a flat-bottomed lake valley between mountains.

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IX · GLACIERS AND THEIR WORK

Ice, as has already been pointed out, covers somewhat more than 10 per cent of the land surface of the globe. The importance of the study of this geological agent, however, does not spring from its present extent or performance; it depends, rather, upon the persisting effects of glacial activity of the past. During the latest of the several ice ages, glaciers of great size rested upon the surfaces of Canada, the northeastern states, Europe, and elsewhere; their combined area, at the time of their greatest extension, was about twice that of present-day glaciers. For intermittent periods aggregating hundreds of thousands of years these great bodies of ice gouged and scoured the rock, moved debris from place to place, and spread out their loads in broad sheets or heaped it into piles of diverse sizes and shapes.

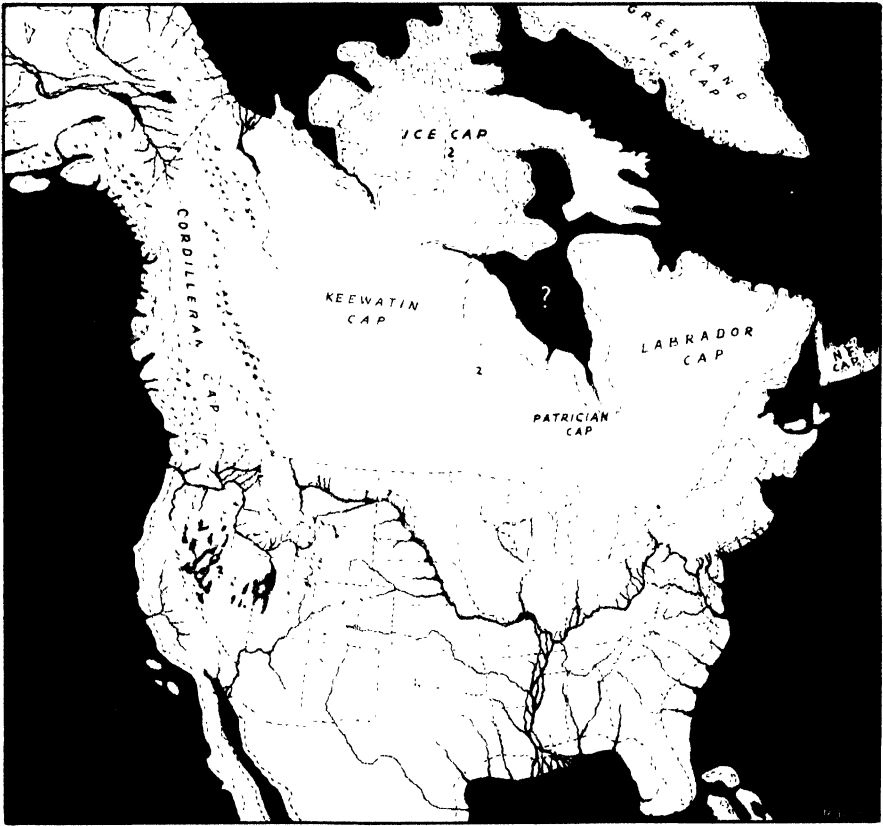
The scenery of the glaciated regions was of course profoundly altered by these activities. It is for this reason, chiefly, that the study of glaciers and glaciation assumes important proportions. It is quite impossible for one uninformed in regard to glacial phenomena to understand the topography of the northern states, Canada, or northern Europe, or that of many mountainous regions in other parts of the world.

The many topographical peculiarities of the northern lands, as well as the presence of rocks which had obviously been transported from distant points, in some instances hundreds of miles away, led early

United States Navy Photograph



Edge of the Antarctic ice sheet. An iceberg drifts off into the Bay of Whales. Antarctica is the coldest and highest of the continents. The South Pole is located on the top of a lofty plateau 10,000 feet above sea level! Five million square miles of ice cover the Antarctic continent—most of what remains of the vast continental glaciers of the recent "Ice Age."



North America in the grip of continental glaciation. At the time of their greatest extension, glaciers of the Ice Age covered practically all Canada and the United States north of the Missouri and Ohio rivers. Several large lakes existed in the Great Basin.

observers to erroneous, and sometimes grotesque, conclusions. Floods, among them the Biblical flood, were called upon to explain the displacement of the smaller rock fragments, while the larger pieces were assumed to have been carried by icebergs across a hypothetical sea, to be dropped upon the melting of the ice. Because of this misconception, this transported material is still referred to collectively as drift.

Most of the credit for solving the mighty puzzle of continental glaciation belongs to the Swiss naturalist Louis Agassiz. Agassiz, who had spent much of his early life among the glaciers of the Alps, had seen ample evidence of rocks which had been torn from the mountain sides, carried downward by creeping ice, and deposited in het-

erogeneous masses. It required but the imagination of his genius to picture the same process on a gigantic scale, with continents laboring under millions of square miles of ice. Today, proofs of Agassiz's belief are universally accepted, and no one doubts that much of the finest scenery of a large part of the world has been fashioned by the slow but persistent action of extinct glaciers.

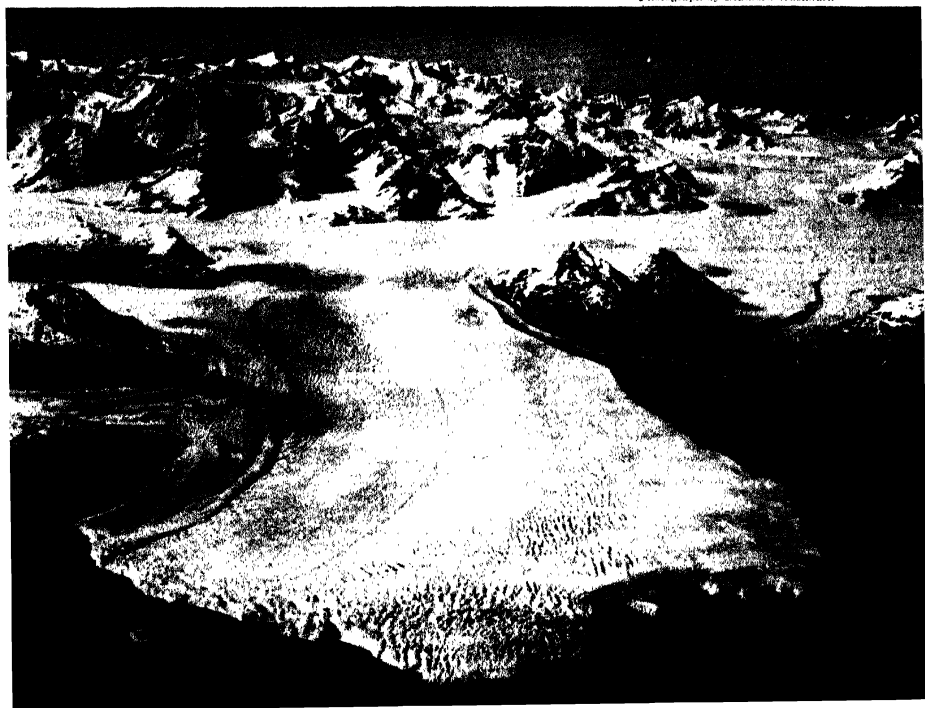
THE ORIGIN OF GLACIERS

Glacial ice is the result of the consolidation of snow. Wherever more snow falls in winter than melts during the summer, it accumulates year after year, forming a *snow field*, and becoming the starting point of one or more glaciers.

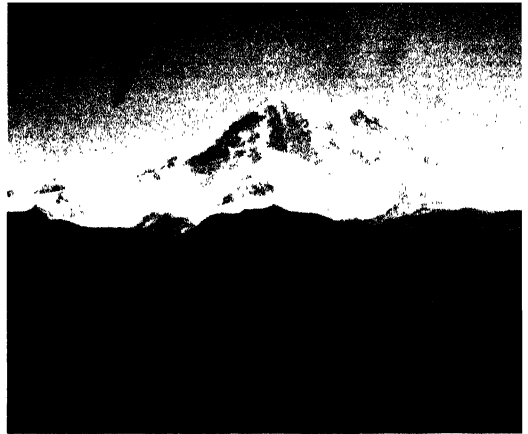
Snow consists of small hexagonal crystals which appear white and opaque because they are mixed with air, causing the reflection of light from numerous surfaces. When snowfalls of many years have been piled one upon another, pressure of the upper layers expels some of the air from the underlying snow, and forces the crystals into closer contact. Some of the snow on the surface melts, and the meltwater seeps downward, forcing out still more air, and eventually refreezing

Columbia Glacier as seen from Prince William Sound, Alaska.

Photograph by Bradford Washburn



The longest valley glaciers in the United States lie upon the surface of Mount Ranier, Washington. Twenty-eight glaciers rest in the hollows of this mountain, the longest being seven miles in length. Only seven of the glaciers have shown movement, which is at the rate of from 1 to 2 feet per day.



Missouri Pacific Railroad

in the form of compact ice. Many of the smaller snowflakes melt, but soon freeze again after joining larger grains. Thus the light, powdery snow is gradually converted into a mass of small granules of ice; in this state the mass is known as *névé* or *firn*. These processes of compression and recrystallization continue until the *névé* is eventually changed into solid ice which, when of sufficient bulk, is forced into a slow motion by the pull of gravity.

Glacial ice often exhibits a stratified structure. This is produced in part by the occasional melting of surface snow, followed by refreezing into a thin sheet of ice covering the *névé* below. In addition, dust is frequently blown upon the surface of the ice, furthering the process of stratification.

CLASSIFICATION OF GLACIERS

Ice sheets. A sloping surface is not necessary to induce motion in a glacier. Movement may originate in a snow field lying upon a perfectly flat plain; instances are known, in fact, in which rocks were picked up from low-lying areas, such as those around Hudson Bay, and were dropped at much higher elevations. Glaciers move in the direction of the slope of the upper surface of the ice. Therefore, if ice of sufficient bulk accumulates at any point, it will begin to flow outward in all directions. A glacier of this kind, characterized by a tendency to motion in all directions away from the point of origin, is called an *ice sheet* or *icecap*. Such glaciers may be very extensive and very thick, covering completely the territory across which they move, except for isolated mountain peaks (*nunataks*) projecting above



Canadian National Railways

A valley glacier of the Canadian Rockies.

the ice. Ice sheets of such size that they would cover a considerable part of a continent are termed *continental glaciers*.

Most of the ice which exists today is organized into the two great continental glaciers of Greenland and Antarctica. The Greenland ice sheet is nearly 1500 miles long and half as wide, covering more than 700,000 square miles of the island with a blanket of ice which is well over a mile in thickness near its center. Although the snowfall of this region is slight, amounting to the equivalent of only a ten-inch annual rainfall, very little moisture is lost through evaporation, because of the low temperatures prevalent. Little is known of the territory which lies beneath this expanse of ice. Where it thins out near the coast, the ice is pierced by lonely nunataks. At its margins the glacier divides into tongues of ice, some of which reach the sea, where they break up into icebergs.

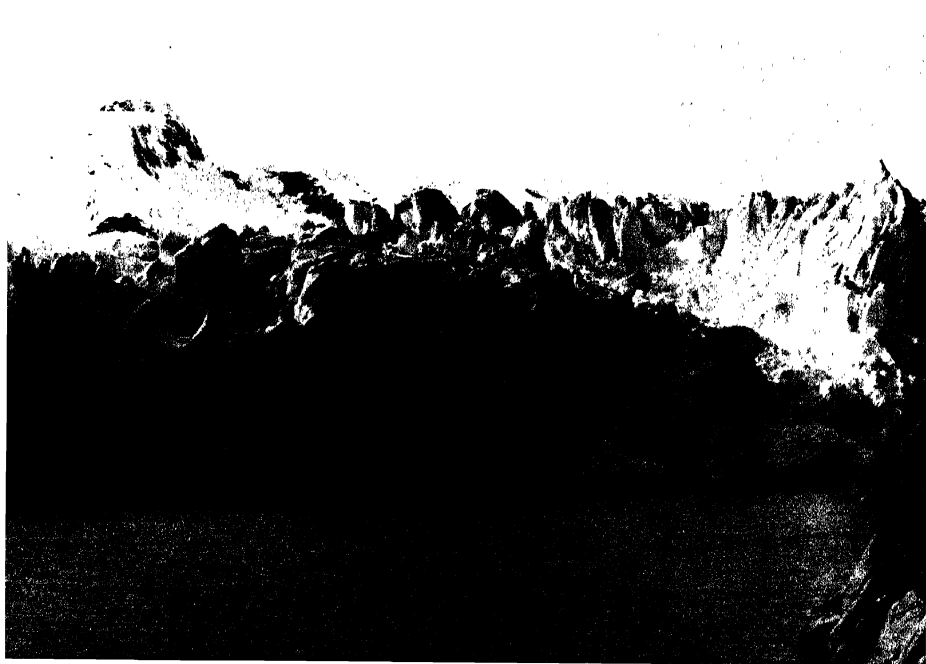
A vast, cheerless expanse of ice with an area of more than 5,000,000 square miles rests upon the surface of Antarctica, spreading out toward all the oceans which border it. Antarctica is the highest of all continents; the South Pole is some 10,000 feet above sea level, and parts of the continent rise at least 2000 feet higher. Along its borders the glacier pushes out into the sea, where it rises and falls with the tide. Part of this floating margin presents seaward a vertical face ranging in height from 50 to nearly 300 feet, known as the great ice barrier. From the Antarctic icecap come the largest of all icebergs. The illustration on page 172 shows a portion of the edge of this great ice sheet from which a huge iceberg has become detached.

Other icecaps are to be found on Norway, Iceland, and elsewhere. Compared to those of Greenland and Antarctica, however, they are all of small size.

Valley glaciers. *Valley, mountain, or alpine* glaciers are those confined by the walls of a valley. They usually originate in a snow field on the tops or on the sides of mountains, and make their way to lower levels through pre-existing valleys. Glaciers of this type, typical examples of which are shown on pages 175 and 176, exist on every con-

Lower end of Taku Glacier, Alaska. Tidal glaciers are the source of icebergs, which effect the transportation of rock debris at sea.

Canadian Pacific Railway





Canadian National Railways



Canadian National Railways

(Left) Glacier of the Angel, Jasper National Park, Canada. Photograph was taken about 1920. (Right) Glacier of the Angel, photographed in 1946. Note by comparison with illustration on the left how the mass of ice has diminished in twenty-five years.

continent except Australia. Although they of course reach their best development in high latitudes, they are not restricted to any section of the globe; glaciers occur in high mountains very nearly on the equator.

Probably the best-known valley glaciers are those of the Alps. The line of perpetual snow lies in the Alpine region between 8000 and 9500 feet, and areas above these altitudes serve as regions of accumulation for snow and the starting points of from 1000 to 2000 glaciers. The Aletsch Glacier is more than ten miles in length, although most of the glaciers of the Alps are not more than one or two miles long. They may descend to altitudes of about 3200 feet.

In the United States small glaciers occur in the Rocky Mountains, the Sierra Nevadas, and the Cascades. In Glacier National Park, an area in northwestern Montana including part of the spectacular Lewis Range, are sixty valley glaciers, as well as abundant evidence of more and much larger ones during the recent geologic past. Many glaciers surround the 14,408-foot summit of Mount Rainier (p. 175), near Tacoma, Washington; some of these are the longest glaciers of the

United States. The present southern limit of glaciers in the United States is in the vicinity of Kern Mountain, California, in the Sierras, a region of exceptionally heavy snows.

Many splendid glaciers occur in the Canadian Rockies and in Alaska. Among the latter the Hubbard and Muir are two of the best-known. These terminate in the sea, where they break off, forming icebergs; such glaciers are known as *tidal glaciers*, an example of which is pictured on page 177.

With a few explainable exceptions, the valley glaciers of the world have been growing shorter during recent years. Whether this signifies a major climatic change or merely a temporary temperature swing cannot as yet be determined. Dramatic evidence of this change is to be seen in the illustrations on page 178 and on this page.

Piedmont glaciers. Intermediate between valley glaciers and ice sheets is a rare type of glacier known as a *piedmont glacier*. As the name indicates, it is formed at the foot of mountains by the confluence

Thinly bedded rocks offer ideal conditions for glacial quarrying. Note also how the edges of these layers have been abraded by the glacier, which was formerly more extended than now.

Great Northern Railway



of a number of descending valley glaciers. The Malaspina, the largest glacier of Alaska, is of this type. The Malaspina is sixty miles long by twenty-five miles in width, covering an area of fully 1500 square miles. Its ice is nearly stagnant, and a number of streams cross its surface, while thickets of spruce and hemlock grow in the rock debris which covers it. The Malaspina and its huge neighbor, the Bering, are fed by many valley glaciers emerging from the adjacent mountains.

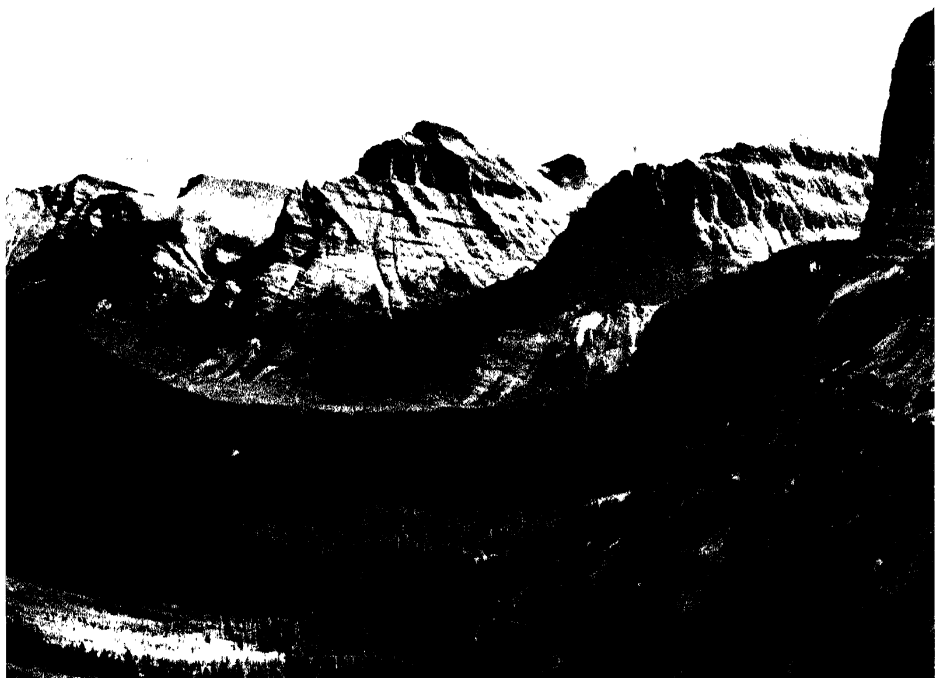
GLACIAL EROSION

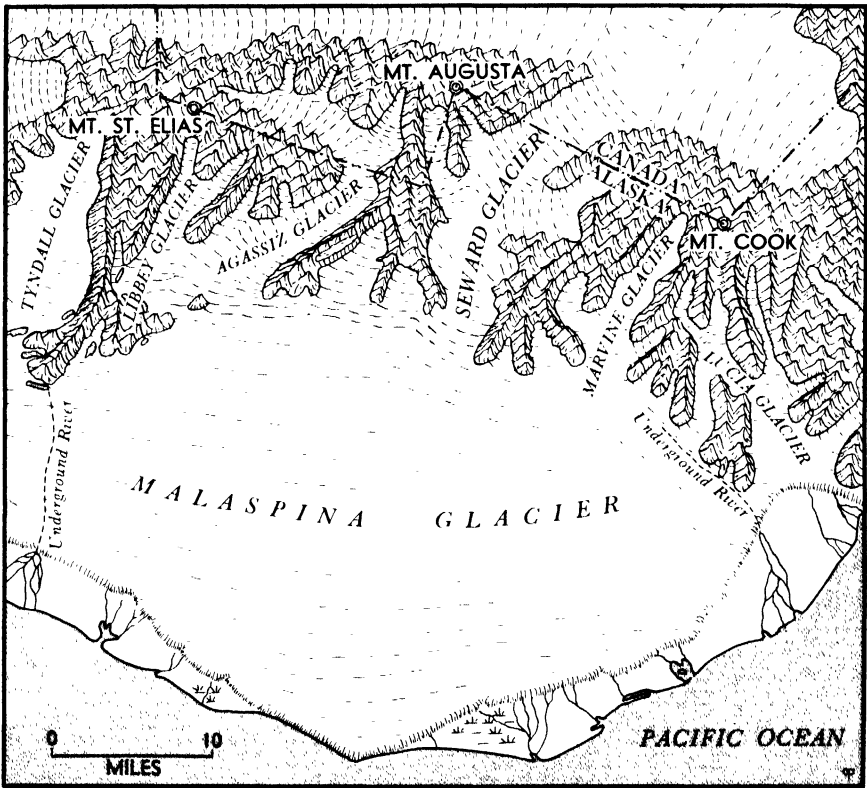
Methods of erosion. The erosive work of glaciers is of two kinds: *plucking*, or *quarrying*, and *abrasion*. By plucking is meant the pulling from place of blocks of rock to which the ice has frozen. The process does not produce important results in smooth, unjointed formations, but it is sometimes very effective in rocks of irregular outline and in those containing numerous cracks into which water can seep and subsequently freeze. The region shown in the illustration on page 179, for example, would lend itself well to this type of erosion. Note also the evidences it presents of glacial abrasion.

Abrasion is effected by means of sand or pebbles frozen in the ice

Glaciated valleys are typically rounded, with few projecting spurs or other irregularities.

National Park Service, photograph by George A. Grant





The Malaspina Glacier covers an area of 1500 square miles.

and carried forward by the glacier. These tools are pressed by the weight of many tons of ice against the bedrock, grinding it smooth, or perhaps leaving it scratched and scarred, depending upon the nature of the bedrock and of the transported materials. Reference to the photograph reproduced on page 184 reveals the appearance of an intensely abraded rock surface.

Results of erosion. A valley which has been subjected to the long-continued action of glacial ice is markedly different in form from one carved out by water. The typical glaciated valley is box-shaped—flat-bottomed or broadly U-shaped—with sides that rise at high angles (note illustrations, pp. 180 and 187). Spurs and other small obstructions have either been cut back or ground away altogether, and minor curves in the valley have for the most part been eliminated.

The upper end of a glaciated valley is blunt, and ends in a semi-circular caviety known as a *cirque* (see photograph, p. 183). Cirques have steep sides, often many hundreds of feet high. They act as catch basins for snow, which feeds the glaciers issuing from them. Thousands of mountain lakes occupy the abandoned cirques of prehistoric glaciers.

The method of cirque formation and enlargement is not thoroughly understood. Water from melting of snow and ice probably settles into the rock around the edges of the base of the cirque. Freezing of this water disrupts the rock, which is removed by quarrying.

Glaciers, like rivers, lengthen their valleys through headward erosion, slowly extending their cirques backward and upward. Eventually a considerable part of the mountain top may be eaten away through the headward creep of a number of cirques. The divides between cirques on opposite sides of a mountain may become thin and sharp. Some of the most impressive of the world's mountain peaks have been fashioned in this manner. Among them might be men-

Cirques eating into the mountains of north Labrador.

Photograph by Alexander Forbes, courtesy of American Geographical Society



A cirque, Alaska. The rugged grandeur of many of the earth's highest mountain ranges is partly due to the ice erosion of cirques which gnaw into the flanks of mountains, leaving sharp peaks or jagged ridges between the cirques. Mountains which are less subject to glacial attack often lack this sharpness of outline.



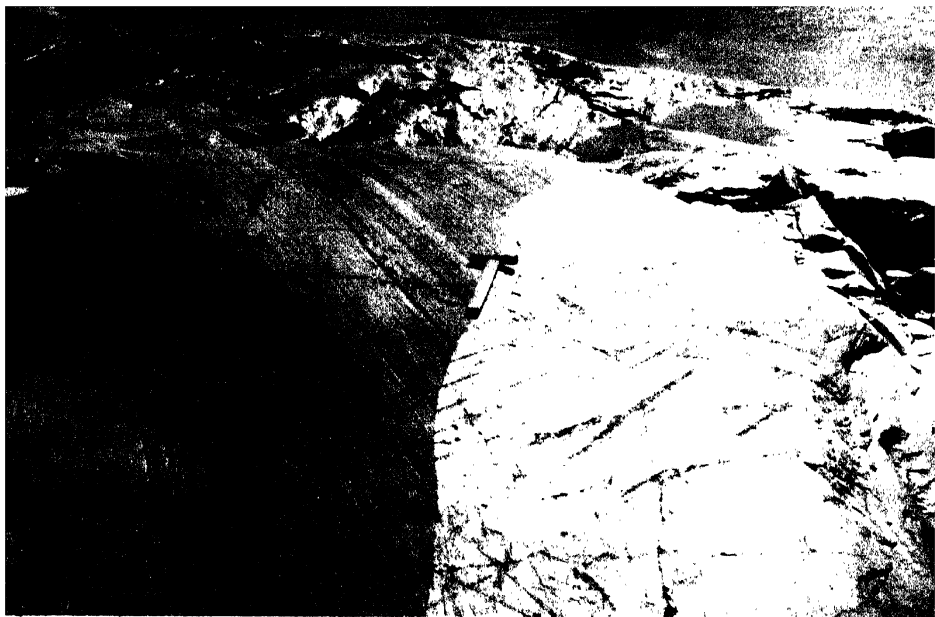
United States Geological Survey, photograph by S. R. Capps

tioned the Matterhorn, Mt. Assiniboine (p. 275), and the Tetons (p. 350).

These features can be observed not only in the accompanying photographs but also to especially good advantage on the greater scale provided by some of the topographic maps. On the Chief Mountain, Montana, map (p. 437), we see a section of Glacier National Park. Note the steep sides (indicated by closely spaced contour lines) and flattened or rounded bottoms (shown by widely spaced lines) of the valleys of Valentine, Waterton, and McDonald creeks; this feature can be observed on practically all of the larger valleys of this section. In contrast, note the narrow bottom and sharp V shape of Johnson Canyon, on the Soda Canyon, Colorado, map on page 447. Numerous steep-sided cirques, many of them now occupied by lakes, are also in evidence on the Chief Mountain map.

While the usual effect of glaciation on a valley is to sand down the floor and remove irregularities, there are occasions on which the reverse is true. In regions of markedly jointed rocks, meltwater may run into cracks and freeze again, giving the glacier a grip on large or small blocks, which may then be pulled out of place. This action in some cases results in a series of smooth, nearly horizontal steps alternating with steep, jagged surfaces, which mark points at which quarrying has occurred.

Sometimes selective quarrying results in leaving a glaciated surface dotted with rounded humps of rock called, from their resemblance to a flock of grazing sheep, *roches moutonnées*, or "sheep rocks." The side of a *roche moutonnée* from which the glacier approaches is subjected to strong abrasion, and hence acquires a smooth, polished, and gently sloping surface. The opposite side, being in a protected position during



Canadian Bureau of Geology and Topography

*Scratched, smoothed, and sanded down; the unmistakable handiwork
of glacial ice.*

Stoss side of roches moutonnées carved out of granite at Lake Shore, Ontario.

Geological Survey of Canada



Roche moutonnée, projecting out of Landing Lake, Manitoba. These asymmetrical rock hummocks, often encountered in large groups, are striking evidences of former glacial conditions. The gradually sloping and the steep, irregular sides of the rock show the direction in which the glacier moved. Many lakes in this area were dammed by glacial debris.



Geological Survey of Canada

the glaciation, is left steeper and more irregular. These features are illustrated in the photographs on page 184 and on this page.

The scratches in the bedrock made by glaciers may be almost imperceptible lines, or they may be great grooves several feet in depth. From them can be inferred the direction in which the glacier traveled.

Hills, like valleys, generally show the rounding and smoothing effects of glaciers which have affected them. A glacier is ever reluctant to turn from its course; a hill will not be evaded if it can be overridden. Small hills, therefore, and even mountains of moderate size, which have been extensively glaciated, will generally exhibit rounded summits; those shown on page 186 are quite typical. It should be remembered in this connection, however, that cirque erosion on the larger mountains usually has the opposite effect.

If sufficient ice be present, a glacier will continue its deliberate gouging, grinding, and plucking at any level—even to and beyond the point at which it may enter the sea. A valley mouth widened and deepened by glacial action which is occupied by the sea is called a *fiord*. Subsidence along a glaciated coast line often contributes to the submergence of the river mouths. Fiords are remarkable for their great depth, which in some cases amounts to thousands of feet. The maximum depth is some distance inland from their mouths, which are generally quite shallow and may be above sea level. The lower Hudson River is a fiord, as is also the St. Lawrence. The fiords of Norway have long been celebrated for their scenic beauty, visible from ships which sail for long distances up the deepened channels between sheer mountain cliffs. Many are to be found along the western coast of South America, and in Alaska, British Columbia, Scotland, Greenland, and elsewhere.



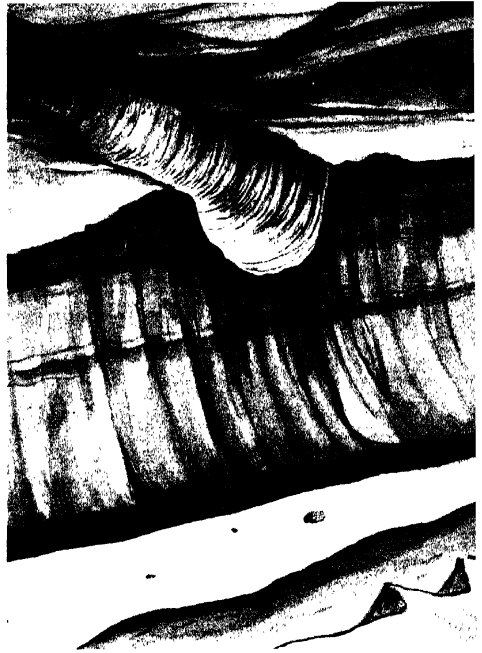
National Park Service, photograph by Allan Rinehart

Hills which have been overridden by continental glaciers usually exhibit rounded contours and very moderate elevations. Their rugged mountain faces have been smoothed away and their steep gorges filled in by glacial debris. These hills have been so recently denuded that they still lack a mantle of soil which will support heavy vegetation. Acadia National Park, Mount Desert, Maine.

Hanging valleys are tributaries which enter their main valleys at elevations above the beds of the latter. They may result from any condition which causes accelerated erosion in the bed of the main stream, such as an increase in the volume of water carried, the encountering of an especially soft or weak rock formation, or the upstream retreat of a vigorous waterfall; but by far the commonest cause of hanging valleys is the deepening and broadening of valleys by the action of glaciers. Glaciers which may occupy the tributary valleys will be comparatively small, and will have but little eroding power; or there may be so little ice in these tributaries that it will not flow at all. In either case, the ice in the main valley is grinding down the valley floor by hundreds or even thousands of feet, and pushing back the walls, perhaps a mile or more. With the disappearance of the glacier, streams again take possession of the system of valleys; a line of waterfalls may result from the enlargement of the main valley, as tributaries pour their waters over the truncated edges of their mouths. Note the diagram on page 187.

Glaciers, especially in their upper and middle courses, often grind out depressions in the floors of their valleys. The cause of this action may lie in the presence of rock that is locally softer than that which forms most of the bed of the glacier. Extensive jointing may also make the rock especially vulnerable in certain spots. In places the channel of the glacier may be restricted, causing the ice to pile up to an exceptional depth. The resulting increase in weight of the ice at one point may cause the erosion of a basin in the rock below.

A hanging valley. The main valley has been deepened more rapidly than its lateral tributary valley. The main valley widened, with the result that the tributary, originally entering the main valley at the same level as that of the latter, has been cut back in its upstream direction. This has brought its mouth into a still higher elevation in relation to the present bed of the main valley. While hanging tributary valleys are generally the result of erosion by valley glaciers, they may be the product of ice sheets, which gouge out valleys parallel to their direction of movement and fill in those which run at an angle to their course. Thus main streams could be deepened and their tributaries made shallower.



Here the path of the Athabaska Glacier takes it over three icefalls. An early stage of glacial erosion.

Canadian National Railways



GLACIAL MOTION AND TRANSPORTATION

The nature of glacial motion. In some particulars the movement of a glacier resembles that of a river; in other respects they differ widely. Like river water, glacial ice does not move as a rigid body, but travels most rapidly in those portions least affected by friction—that is, in the upper and the central parts. Like a fluid, also, the glacier tends to spread out into a thinner sheet upon leaving the confines of a valley and emerging upon a plain.

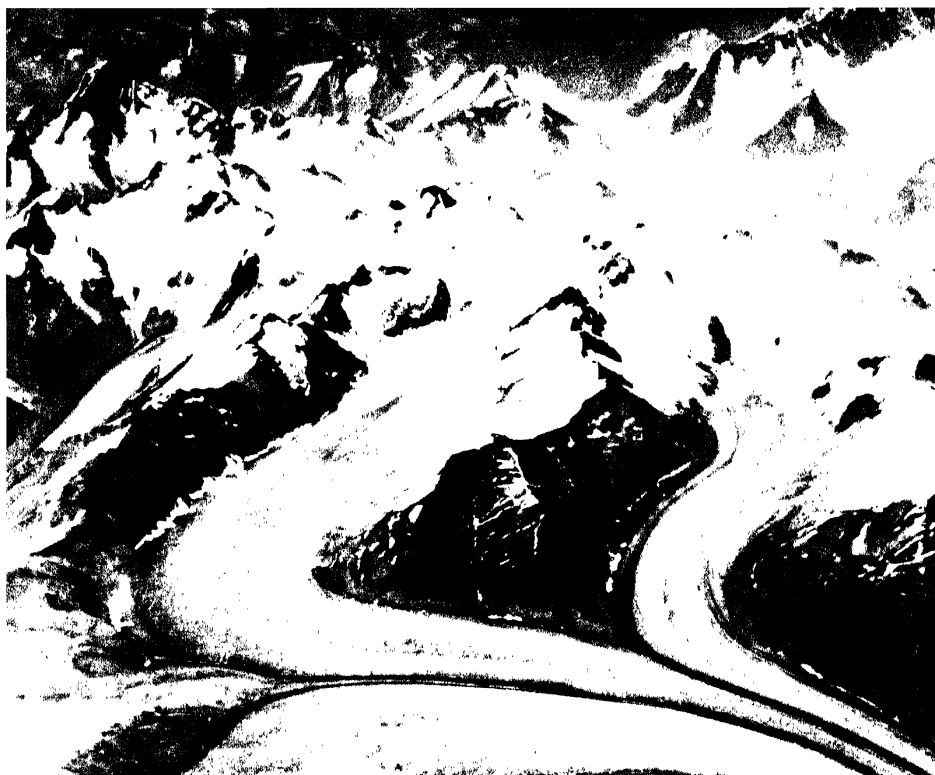
That the movement of glacial ice is not a simple flow of an extremely viscous liquid, however, is demonstrated by a number of its characteristics. Open cracks commonly occur in the ice, and glaciers frequently flow past the empty mouths of tributary valleys without showing any tendency to enter them; some glaciers are known, in fact, which do not completely fill their valleys laterally, but move with unsupported vertical sides. The direction of motion of a glacier does not always conform to the topography, as does that of a stream; the glacier's motion is determined by the slope of the upper surface of the ice, which does not necessarily coincide with that of the ground underneath.

The rate of motion of most glaciers amounts to from a few inches

Crevasses in Blackfeet Glacier, Glacier National Park.

National Park Service, photograph by Hilleman





Royal Canadian Air Force

The lateral moraines of three glaciers merge to form two medial moraines.

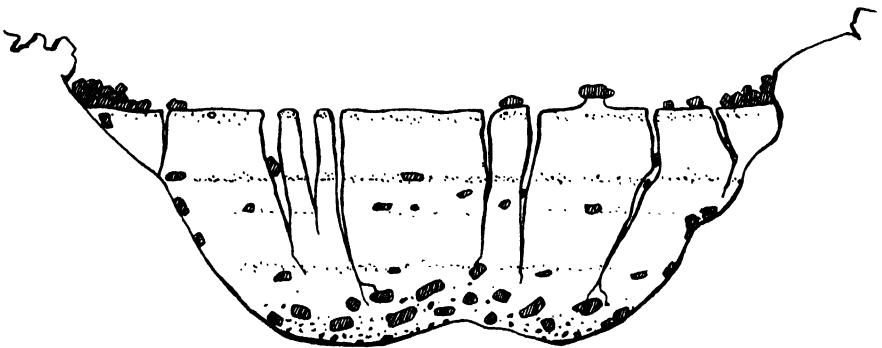
to a few feet per day. Instances have been reported of Alaskan and Greenland glaciers moving at remarkable speeds, in the neighborhood of one hundred feet a day. The rate of movement is markedly affected by temperature. High temperatures weaken the ice, and reduce its resistance to distortion. Glaciers therefore move more rapidly in summer than in winter, and more rapidly by day than by night. Some glaciers have been found to progress with a pronounced jerky motion, periods of relatively rapid and slow movement alternating several times a day.

The fundamental nature of glacial motion is complex, and cannot be said to be thoroughly understood, in spite of extensive investigations to which it has been subjected. Much of the movement appears to involve the melting of ice, either on the surface as a result of exposure or internally as a result of pressure, followed in each case by refreezing. The pressures produced by the freezing of the water, which may have migrated to lower levels while in the liquid state, produce

a thrust which results in motion of the ice, largely in a down-slope direction. Ice, like other rock, also undergoes a mass deformation under slowly applied pressures (see page 388), brought about by a forced rearrangement of crystals or molecules; melting of parts of crystals at their points of contact facilitates this process. Some of the movement of a glacier is probably the result of shearing movements of the upper parts of the ice over the lower, the flow of which is impeded by friction with the bed and by heavier loads of rock debris.

The ice near the surface of a glacier is more rigid than that at deeper levels, as is indicated by the fact that numerous cracks are commonly present in the upper parts, but do not usually extend very deeply into the interior. *Typical* glacial motion seems to occur principally in the lower region, where pressures are greater, the upper ice being largely carried along by the flowing substratum.

Effects of motion upon the ice. The surfaces of many glaciers are exceedingly rough. This roughness is partly the result of differential melting, but is largely due to various accidents arising from the movement of the glaciers over their beds. A glacier not infrequently passes over a cliff or precipice, constituting an *icefall*. The ice of course breaks up into many pieces at such points, the pieces fusing together again at the base of the cliff in a very disordered, confused mass. Peaks of ice projecting above the glacier surface are known as *séracs*.



Glacial transportation. Cross section of a glacier, showing lateral and medial moraines, englacial drift, glacier table, and rock carried at base of ice. Crevasses show one way in which the englacial drift may gain access to the interior of the ice, while the stratified form in which part of this drift occurs points to alternating snowfalls and dust storms.



Ward's Natural Science Establishment, Inc.

Strikingly different effects are produced by different agents of erosion. The smooth facets meeting in lines and points exhibited by the three rocks shown on the left are the work of wind, operating under arid or semiarid conditions; the piece of granite in the center acquired its rounded shape as a result of attrition in a stream bed; while the smoothed and blunted shapes and the striations of the rocks shown on the right mark them as glacial erratics.

A deposit of till, Columbia County, Wisconsin.

United States Geological Survey, photograph by W. C. Alden





United States Geological Survey, photograph by W. C. Alden

Drift which has been worked over by water. Worcester County, Massachusetts.

Erratic boulders resting on surface polished by glacial action. Yosemite Valley.

National Park Service



Wide expanse of moraine topography in Saskatchewan, Canada—the site of glaciation on a grand scale. Here repeated visitations of the great ice sheets of the recent and not so recent past have left the country covered with morainic materials of all kinds, forming an extremely irregular surface of rounded ridges and mounds. In such a region, normal drainage will have been almost completely destroyed, and depressions in the till sheet will form lake beds by the thousands.



Geological Survey of Canada

Another effect of glacial motion is the formation of large cracks or *crevasses* in the ice. These may be the result of lateral bending of the glacier in its course, or of its passage over an irregularity in its bed. Movement across a convex bulge in the rock beneath it, for example, will cause stretching of the surface portions of the ice, and fracturing transverse to the direction of motion will result. As the glacier continues to move over the same irregularity, a series of crevasses may mark the glacier below this point. Such a series in the Blackfeet Glacier of Montana is shown in the illustration on page 188. The size of these crevasses may be estimated by comparison with the human figure.

A crevasse may be melted wide open by the sun and by water running into it. Into the open cavity thus formed meltwater carries particles of rock and earth. This opening in the ice is termed a *moulin* (mill); the turmoil at the bottom may reach the rock beneath the glacier, scouring out depressions in it known as *glacial potholes*.

The carrying power of a glacier. While the quantity of foreign material transported by a glacier is usually much less than that carried by a river of similar size, the ability of the glacier to move rocks of *large* size is enormously greater. The carrying power of the glacier, unlike that of the river, is unrelated to its velocity; hence it carries microscopic particles and great boulders with equal ease.



Illinois Geological Survey

Easily recognizable glacial topography, resulting from the deposition of moraine and till. If the normal drainage has not been too seriously interfered with by the glacial deposits, terrain such as this may constitute excellent farming country.

The glacier's load. A glacier transports material upon its surface, within the ice, and at its base. Light materials, dust and sand, are blown upon the ice by the wind. On the surface of ice sheets travel boulders plucked from the tops and sides of projecting nunataks. These rocks, of all sizes, trail away from the peaks from which they were torn in long lines, known as *boulder trains*.

When organized into definite masses, the loads of glaciers are known as *moraines*, a term also applied to certain glacial deposits. Material which has slumped upon the sides of a valley glacier as a result of undercutting or other cause forms long ridges along each lateral margin, and is known as *lateral moraine*; the same term is used to denote the structure formed of this material. These ridges may build up to a height of several hundred feet, although such extreme heights are usually due to the presence beneath the fragmental material of ice walls of considerable size, which were protected from sun and wind by the morainic material above them, and consequently did not melt down as did the exposed central parts of the glacier.

Since most glaciers occupy former stream valleys, there are many instances in which glaciers unite with one another, just as did the streams whose valleys they have pre-empted. In these cases the lateral moraines along the merging sides also fuse, forming a band of debris which from the point of junction downward is not located along the margin of the ice, but is carried along somewhere within its borders, as is clearly shown in the photograph on page 189. This ridge is then called a *medial moraine*. In a glacier formed by the confluence of several tributary glaciers, several medial moraines will usually be present, each representing the acquisition of an additional tributary. Medial moraines do not generally retain their identity as well as lateral mo-

raines, since they do not continue to receive fresh supplies of material; as the glacier melts down their constituent particles gradually disperse.

As the glacier progresses, it freezes to much rock material, which is carried frozen in the ice of its base or its sides. *Englacial drift*—material carried within the body of the glacier—finds lodgment in the interior of the ice in various ways; surface material, such as that spread by winds, may be buried deeply by successive snows; rocks may fall or be washed into crevasses; particles may become detached from rock masses which project upward into the glacier from below. Englacial drift is seldom abundant, most of the ice, except that near the bottom, remaining nearly free from mineral matter. A careful study should be made of the diagram on page 190, in which these kinds of drift are shown in their typical relationships.

Rocks which have been transported from one place to another by glaciers are known as *erratics*. Most erratics show no effects of transportation by the ice. Those which were carried on the bottoms or sides of a glacier, however, are usually easily recognizable. They will exhibit smoothed (but not rounded) surfaces, with blunted edges. They will also show scratches (*striae*) acquired by contact with the glacier's bed. These features are shown in the erratics in the photo-

The glacier advanced from the left, leaving two parallel ridges of terminal moraine, and beyond them a sweeping outwash plain. LaPlata County, Colorado.

United States Geological Survey, photograph by Whitman Cross





United States Geological Survey, photograph by W. C. Alden

Kettle holes such as this often result from the melting of ice blocks buried in the morainic material and the subsequent slumping of overlying rock debris.

graph on page 191. This picture and the legend beneath it should be carefully studied in order to understand the differences between rocks transported by different agencies.

GLACIAL DEPOSITS

Deposits made by glaciers may be grouped into two classes, those made by ice alone, and those formed through the co-operation of running water. Deposits of the former class are entirely unsorted and unstratified, and are known as *till*. The latter may be termed *glacio-fluvatile* deposits. A comparison of the pictures on pages 191 and 192 will serve to show the differences between these two types of deposits. Most glacial deposits are light in color, and many are remarkable for the wide variety of the rock fragments they contain. Fossils are rare or absent.

Moraine deposits. At the lower terminus of a glacier an elongated, curving, usually discontinuous belt of *terminal moraine* is built up, constructed of everything carried to and dropped at this point. The moraine proper is structureless, and consists of rock debris of all sizes and of different kinds. Striated pebbles or boulders will be present, although in most cases they are not common. The surface of the moraine is often pitted with depressions known as *kettles*, cavities produced usually by the melting of isolated blocks of ice which had been surrounded by or embedded in material of the moraine. As a glacier slowly melts back toward its source, a series of moraines of this kind may be left, marking points of hesitation during the retreat. Deposits so made are called *recessional moraines*.

The Whitewater, Wisconsin, map on page 450 shows a diagonal band of terminal moraine. This is but a small portion of the entire deposit. Note the kettles, shown by depression contour lines. Note also the two bands of terminal moraine, shown in the photograph

reproduced on page 195, with an outwash plain extending from them toward the right. A kettle hole, in typical surroundings, is shown on page 196.

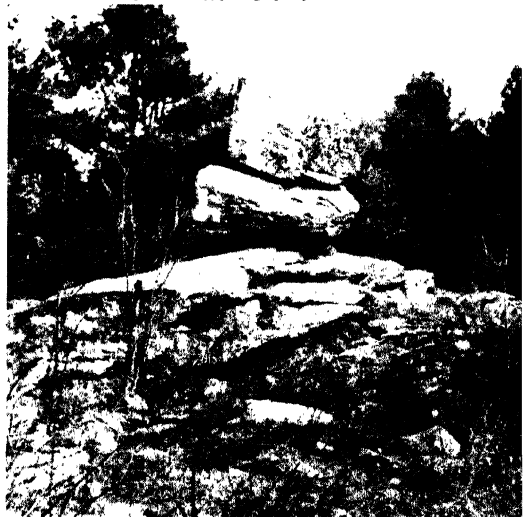
Most conspicuous of a valley glacier's deposits are often the lateral moraine ridges, left standing along the valley sides. These in general resemble the terminal deposits in structure and composition, though not in their relation to associated structures; so also do such remnants of medial moraine as may have escaped the disintegrating effects of transport and the melting of the supporting ice.

Deposition also takes place at the bottom of actively moving ice. If this portion of a glacier is overloaded, so that friction develops with the underlying rock, less energy may be required to override parts of the load than to drag it along. Under these conditions boulders, sand, and clay, in a completely unassorted state, may be dropped. This type of deposit, known as *boulder clay*, may accumulate to a considerable thickness. Added to it, upon the melting of the glacier, is the similarly heterogeneous collection of rock material which was scattered upon, within, and beneath the ice. All of this debris is spread in a broad, very irregular sheet across the former path of the glacier; it constitutes what is known as the *ground moraine*.

The till of former glaciers may be found scattered widely over most of the territory north of the Ohio River. Some of it is hundreds of miles from its point of origin. Certain erratics, such as those depicted on this page, give eloquent testimony of the size of the glaciers which once occupied this area. One of them at Nottingham, New Hampshire, is 60 feet long, 40 feet wide, and 40 feet high, and is estimated to weigh 6000 tons. A still larger boulder of this kind, located at

Perched boulders, Massachusetts, dropped in this position by an extinct glacier. Erratics or "lost rocks," often found many miles from bed-rock of a similar nature, greatly puzzled early American geologists. Freaks, like the one at the right, must have been especially difficult to explain. Erratics of immense size occur frequently in New England.

United States Geological Survey, photograph by W. C. Alden





Canadian Bureau of Geology and Topography

Drumlins in Alberta, Canada. The origin of these curious hills is one of the mysteries attending glaciation. They are generally formed near the end of glaciers. The clay content of drumlins seems to contribute the cohesive property necessary for their formation. Their streamlined form usually indicates strenuous ice flow.

Madison, New Hampshire, measures 30 by 40 by 90 feet. Many other huge erratics exist in New England, while in Europe ice-transported boulders several hundred feet in length are known.

Drumlins. A special case of subglacial deposition is to be found in the formation of *drumlins*. These are smooth, elliptical hills, seldom exceeding one-half mile in length or 100 feet in height, although a few of them attain dimensions twice as great. The "upstream" or stoss side of a drumlin is steeper and blunter than the lee side. Most drumlins consist of till throughout, although some are molded over cores of bedrock. The presence of a large proportion of clay in the bottom load of a glacier seems to be a necessary factor in the formation of these structures.

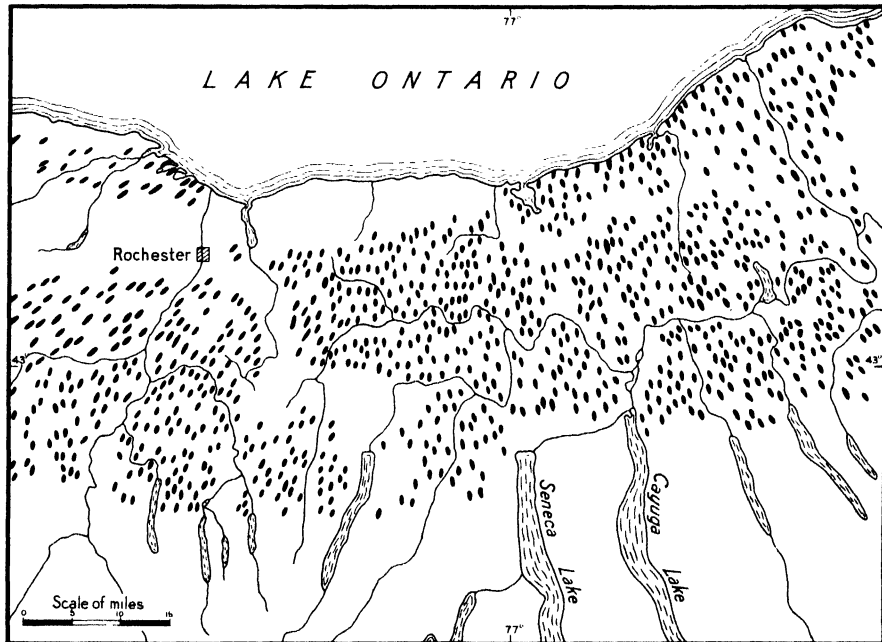
Drumlins commonly occur in groups, with their long axes parallel to the direction of motion of the ice; sometimes they exhibit a tendency toward radial arrangement. At least six thousand of them are to be found in New York state. Other large groups occur in eastern Massachusetts, southeastern Wisconsin, northern Michigan, and the British Isles. A comprehension of the manner of grouping can be gained from a study of the section of the Weedsport, N. Y., map reproduced on page 449. The group shown here is but a very small part of the entire assemblage. A photograph of a Canadian drumlin is shown on this page.

Eskers. Turning our attention to glaciofluvial deposits, we find conspicuous among these certain long, narrow, steep-sided ridges consisting of gravels and coarse sands, poorly sorted and stratified. These *eskers* occupy areas formerly covered by extensive ice sheets. They

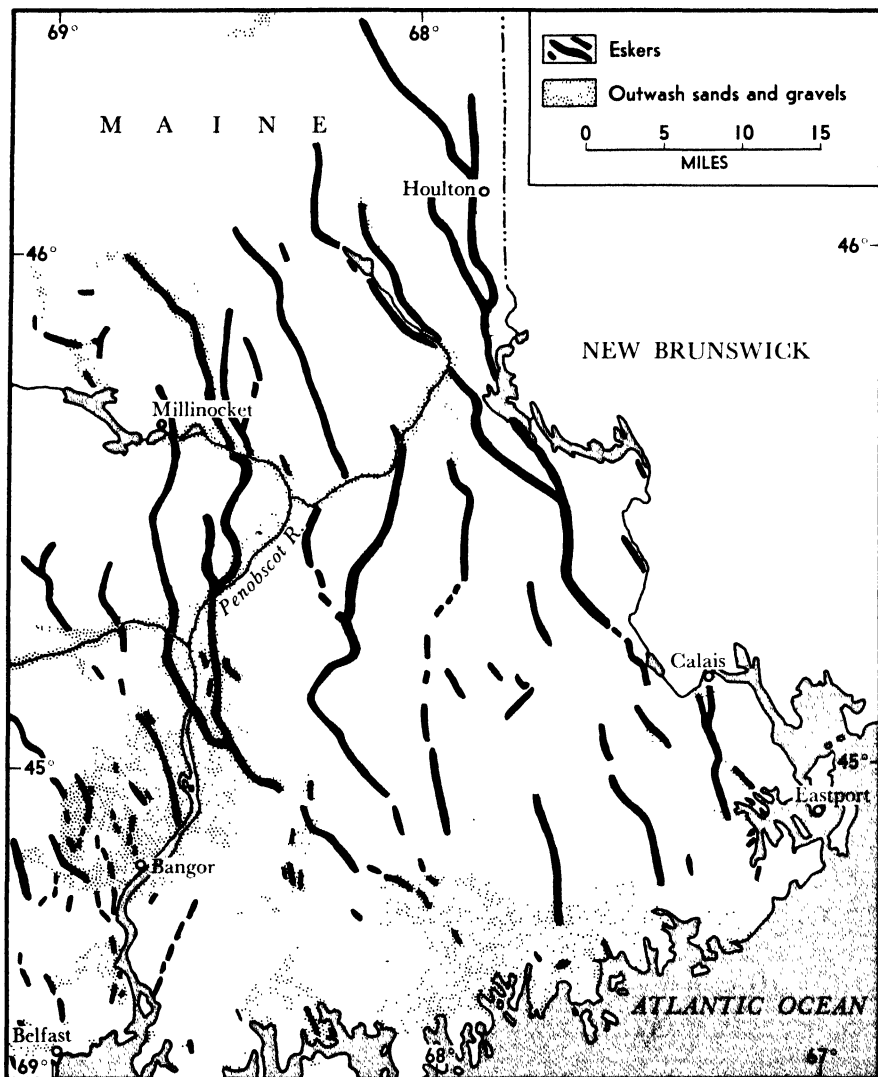
may be more than 100 miles in length, and up to 150 feet high; they branch and wind about like stream valleys, and in places exhibit a "braided" structure. That they are not ordinary channel deposits is shown not only by structural differences, but more plainly by their courses, which show no respect for topography, crossing normal drainage patterns at any angle and passing up and over hills, some of them hundreds of feet high. Eskers are believed to be deposits laid down in streams running through tunnels in or under the ice, and thus subject to hydrostatic pressure. They are known in Canada, Minnesota, Wisconsin, Michigan, Illinois, and elsewhere.

The general appearance of an esker is shown in the illustration on page 201, and the shape and relation to topography by the aerial photograph appearing on page 202. The latter photograph also gives a good impression of strongly glaciated topography.

Resembling eskers but rarely more than a mile in length are ridges known as *crevasse fillings*. Since these consist of debris washed into open crevasses in the ice, the water by which they were deposited was under no special pressure; such fillings consequently are likely to retain more fragments of small diameter than eskers ordinarily do.



Drumlins and glacial lakes south of Lake Ontario, in New York State.



Eskers and outwash deposits in the southeastern part of Maine.

Kames. While eskers are deposited in the upstream section of a glacier, most glaciofluvial material is laid at and beyond the lower end of the glacier. Among these latter deposits we find numerous irregular, roughly stratified hills called *kames*. These structures consist chiefly of gravel and sand, and are quite generally of an imperfectly conical shape; these characteristics suggest that they are deposited by

streams as a sort of glacioalluvial fan, spreading out at the end of the ice and losing their finer constituents in the rapidly escaping water. They are strongly cross-bedded, with layers inclined at high angles, in some cases as much as 30° , indicating a very sudden decrease in the velocity of the stream which deposited them. Although very irregular in distribution, they are frequently found on the stoss side of a terminal moraine, where they appear to have been built up between the moraine and the end of the ice. This theory is borne out by the fact that stratification has in most cases been destroyed by slumping on the side formerly in contact with the glacier, presumably because of loss of support due to melting of the ice.

Elongate glaciofluvial deposits laid down by streams which flowed between the sides of a glacier and the valley walls are called *kame terraces*.

Outwash deposits. Water issuing from a melting glacier breaks through low places in the terminal moraine, carrying sediment out upon the surrounding country. At the points of emergence much of this material is laid down in the form of fans, which merge to form a broad *outwash plain* (see illustrations, pp. 195 and 203). The slopes

An esker deposited by a stream confined within or beneath an extinct glacier.

Canadian Bureau of Geology and Topography





Royal Canadian Air Force

An esker crossing an intensely glaciated area.

of outwash plains are lower and the materials of a finer grade than those of kames, and sediments are better sorted and stratified. The surface may be fairly smooth, but it is very often intensely roughened by knobs or knolls and pitted by kettle holes, which may be from a few feet to several miles in diameter.

An outwash deposit occupying the lower end of a valley is called a *valley train*. A deposit of this kind, however, may extend for miles beyond the end of the valley.

Glacial-lake deposits. During the melting of a large glacier many lakes and ponds exist in hollows in its outwash plain. Others occur between the end of the ice and the terminal moraine, and in valleys which have been dammed by terminal or recessional moraines. The deposits formed in these bodies of water decrease in thickness and in the coarseness of their constituents with distance from the glacier, thickness of deposits and coarseness of texture showing a definite correlation.

During the summer season, water from the melting glacier is abundant, and deposits much silt in bodies of standing water. The silt is spread out into a light-colored band, usually something less than one-

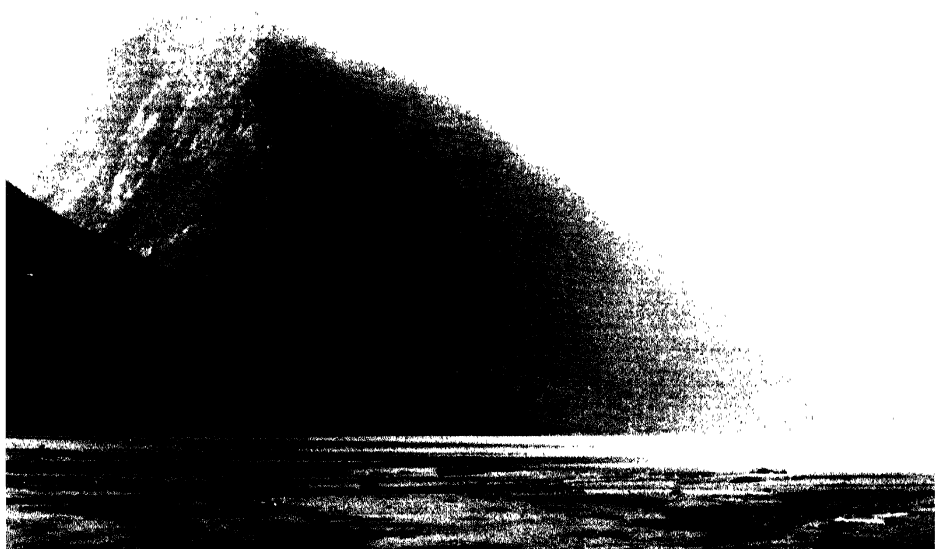
half inch in thickness. As winter approaches, the amount of water reaching the lakes and ponds is diminished, and finally ceases altogether as the water freezes. During this period only fine clay and organic particles settle to the bottom, forming a thin, dark layer. Each pair of these layers constitutes a *varve*, which presumably represents deposition taking place during one year's time.

Summary of glacial deposits. Sediment deposited entirely by ice is unstratified, and of heterogeneous composition. It consists in many instances of rock fragments of widely differing character, of which some may exhibit striations and bluntness of shape. Deposits laid by waters issuing from the melting ice are more or less assorted, the coarsest material finding lodgment nearest the glacier.

Terrane covered by ground moraine is usually very rough or irregular, and may be crossed by eskers and dotted with drumlins; both of these features are indicative of the activity of moving ice. Between the glaciated and unglaciated territory will be found a belt of terminal moraine, frequently bordered on the stoss side by numerous kames, which slump toward the glaciated section. Beyond the moraine are the stratified and often pitted outwash plains. The presence of kettles in any part of a deposit is proof that the ice at that place was stagnant, and therefore helps to identify terminal moraine or outwash deposits.

Outwash plain. Near Bella Coola, British Columbia.

Canadian Bureau of Geology and Topography





Topographic structures in front of a glacier. The glacier shown here has retreated from the position marked "ice contact wall."

This association of sediments is important in distinguishing glacial deposits from those of certain other agencies, such as landslides and mudflows. Lack of stratification and the presence of striations on some of the constituents of the deposit, usually taken as proof of glacial origin, are not in themselves conclusive.

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X · THE OCEAN



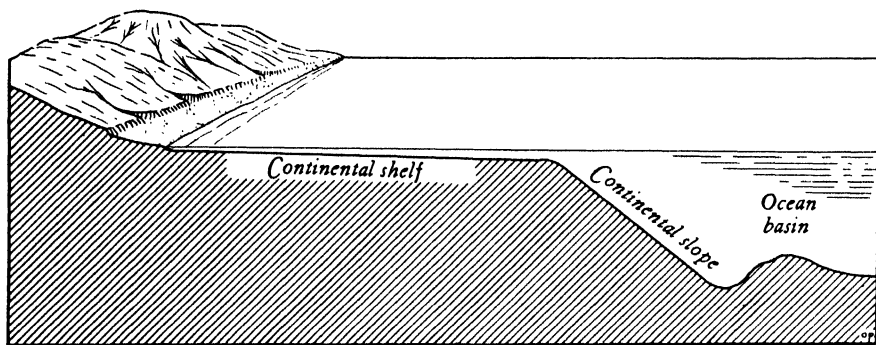
Three hundred and twenty-five million cubic miles of water fill the great ocean basins of the earth. The oceans cover approximately 72 per cent of the surface of the globe, 61 per cent of the northern hemisphere, and 81 per cent of the southern. The average depth of the water is just about five times the average elevation of the continents. If the surface of the lithosphere were that of a smooth sphere, a universal ocean would cover the earth to a depth approaching two miles. The quantity of water in the oceans, in fact, is almost fifteen times as great as that of all the rock of the continents and islands above sea level.

The importance of the ocean to the living inhabitants of the earth could hardly be overstated; indeed, man's frequent references to mother earth might well be supplanted by the concept of "mother ocean," for it was from the sea that life originally came, and one of the indispensable factors in its continued existence on the planet is the earth's great belt of water.

Because of the exceptional capacity of water for absorbing heat, the oceans exert a moderating effect upon the temperatures of the entire earth, taking up excessive quantities of heat and paying it out slowly. Ocean currents are also of the greatest importance in the distribution of heat over the globe. Were it not for these stabilizing effects of the oceans, terrestrial temperatures would in all probability frequently exceed the precariously narrow limits within which life is possible. Most of the water vapor for the rainfall upon which land life depends also comes from the ocean reservoirs.

THE OCEAN BASINS

Marginal features. The ocean basins occupy about two thirds of the earth's surface area, and are not of course true basins, as their beds are convex, like the surface of the sea. They are somewhat more than full, some water encroaching upon the borders of the continental platforms. The surfaces upon which this comparatively shallow epicon-

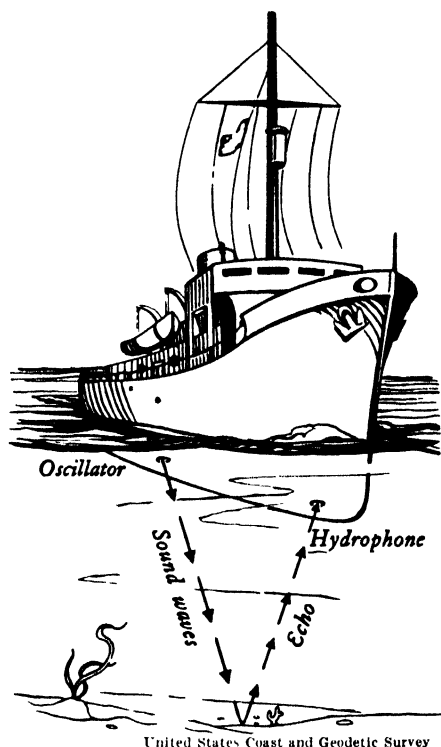


The edge of the continent. Limitations of space make it impossible to portray these features in their actual relationships. In most places the continental shelf is proportionately much wider than here indicated, inclinations of both continental shelf and continental slope are greater, and the trench at the bottom of the slope is deeper.

Continental water rests, 10,000,000 square miles or more in extent, are called *continental shelves*. Their width varies considerably, depending largely upon the stability of the coastal region in question. If unaffected by recent vertical movements, the continental shelf slowly enlarges through the wearing back of the continents by waves, and through the addition of sediment to the seaward edge of the shelf. Thus the Arctic coast of Siberia is featured by a continental shelf which attains the extraordinary width of 300 to 400 miles, and the Grand Bank of Newfoundland, famous as one of the world's greatest fishing grounds, is a section of shelf that extends fully 250 miles east and south of Newfoundland. Along the Atlantic border the width of the continental shelf generally varies from fifty to seventy-five miles, although it is much narrower than this off the coast of Florida. On the west coast the shelf is in places no more than five miles wide, although it reaches a somewhat greater width near the Canadian boundary. The general narrowness of the continental shelf along the Pacific is due chiefly to recent uplift in that section.

The seaward slope of the continental shelves is very gentle, amounting on the average to something like ten to twenty feet to the mile. Their outer edges are marked by an abrupt increase in steepness; this sharper declivity, beginning at a depth which in most places approximates 600 feet and attaining a width which in general is somewhat less than that of the shelf, is known as the *continental slope*, and can

The speed of sound measures the ocean's depths. Soundings were taken by the Romans and other ancient peoples by lowering weighted lines to the bottom. Columbus, sounding the Sargasso Sea, dropped a cannon ball tied to a rope 200 fathoms long. Sounding the Nero Deep near Guam (31,614 feet) required almost six hours! Without the invention of the sonic method, the contours of the ocean bottoms would have remained a mystery to man. Now the greatest depths can be probed in about fifteen seconds. Sound waves travel about 4400 feet per second, their speed varying a little with the pressure and salinity of the water.



be regarded as the true edge of the continent which it borders. These relatively sharp slopes extend in some places into depths which number among them some of the deepest abysses of the sea. Since these structures cannot be shown in their correct proportions in a diagram, study of the illustration on page 206 should be conducted with full understanding of the limitations mentioned in the legend.

The ocean depths. Up to the beginning of the nineteenth century no one had any clear idea as to how deep the ocean really was. It is said that Magellan believed that he had discovered the deepest spot in the ocean in 1521 when his sounding line, which may have had a length of several thousand feet, failed to touch bottom. Sounding the greater oceanic depths was a tedious and time-consuming task; even with the most modern motor-driven equipment, making a sounding with a weighted line may require several hours' time, during which the ship must of course remain stationary. With the invention of the sonic, or acoustic, method, whereby the length of time required for a

sound to travel to the sea bottom and rebound to the surface is translated into feet or fathoms, a much fuller knowledge of ocean depths has been obtained than would otherwise have been possible. By means of this method soundings have become a matter of seconds rather than hours, and they do not interrupt the motion of the ship. Many thousands of sonic soundings have been made of the ocean depths, especially in the Atlantic.

The Pacific Ocean, containing more water than all other oceans combined, is much the deepest; its average depth is 14,050 feet. The Indian Ocean ranks second in this respect with a depth of 13,000 feet, and the Atlantic follows with 12,880 feet. The average depth of the Arctic is in the neighborhood of 4000 feet.

Parts of the ocean floor which are more than 18,000 feet below sea level are known as *deeps*, and the maximum sounding measured in a deep is called a *depth*. About sixty deeps are known, more than half of them in the Pacific. Some are of vast extent; the Murray Deep in the North Pacific, for example, has an area of more than one million square miles. Some of the deepest parts of the ocean are elongate valleys or troughs known as *trenches*, which are characteristically located near the continental borders, often parallel to folded mountain systems; such a development is especially marked in the Pacific and Indian oceans. The deepest point thus far discovered is in a great trench, the Mindanao Deep, that skirts the Philippine Islands (Latitude $9^{\circ} 41' 18''$ North, Longitude $126^{\circ} 50' 50''$ East); it contains one depth of 35,433 feet which is known as the Emden Depth. The deepest sounding in the Atlantic, taken in the Milwaukee Deep north of Puerto Rico (Latitude $19^{\circ} 36'$ North, Longitude approximately $68^{\circ} 20'$ West), shows a depth at this place of 30,246 feet.

The sea floor. In comparison with the land surfaces, the tops of the continental shelves are smooth in the extreme. Not only are these sections protected from the wear and tear that affect the land, but such irregularities as may occasionally appear are subject to removal or reduction by the sweep of currents and waves, or to filling by drifting sediments. Upon the assumption that these or similar factors were generally operative over the deeper parts of the oceans as well, the sea beds were in former times often described as monotonously smooth expanses of remarkably slight relief, a conception to which the early

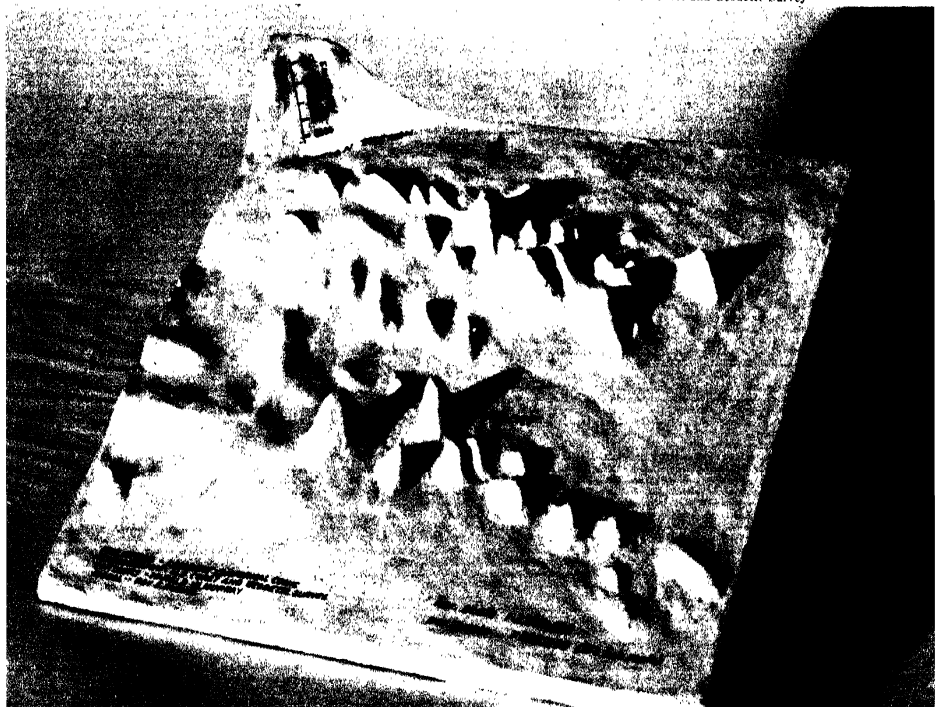
meager data on deep-sea sounding were incapable of offering contradiction. It was even said that, were the waters of the Atlantic to be drained away, one could travel from Europe to America over slopes too slight to be detected by the senses.

While it is undoubtedly true that the ocean basins lack the ruggedness and diversification of relief exhibited by the land surfaces, they can no longer be pictured as the flat, interminable plains they were once considered. In addition to the deeps already described, relief is provided by the presence of great rises, such as the Mid-Atlantic Ridge, which extends in a north-south direction for nearly the full length of the Atlantic. Volcanoes and islands of volcanic origin are numerous, especially in the Pacific. Broad plateaus, parallel ridges resembling mountain ranges, and precipices a mile in height have been discovered.

It is only since the extensive application of the acoustic method of sounding was begun, however, that the intricacy of the relief of certain parts of the ocean bed has become known. Off both the Atlantic and Pacific coasts of North America sonic soundings have revealed continental slopes in a pronounced state of dissection. Submarine valleys

The sea floor is by no means as flat as was once supposed. This relief model shows a group of submarine mountains in the Gulf of Alaska.

United States Coast and Geodetic Survey



have been found which encroach upon the continental shelves, descending down the slopes to depths of thousands of feet. Are these the remains of long-submerged river systems? The Hudson River channel can be traced downward over the continental slope to a depth of 2000 feet, and a channel emerging from the mouth of Chesapeake Bay has been followed to well beyond the edge of the shelf.

But elsewhere, as in Bering Sea and off the California coast, soundings have revealed canyons the origins of which are as yet quite problematical. (Illustrations, pp. 212 and 267.) One such canyon offshore from Monterey dips precipitously from a depth of 300 feet to a level 8400 feet below the level of the sea. While the view that these submarine valleys, some of them comparable to the Grand Canyon of the Colorado in depth and width, have been carved out by the action of running water is held by some geologists, others consider them the products of ocean currents, or of the slumping of accumulated sediments.

OCEAN WATER

Composition. The ocean is a limitless reservoir of the waste from the land. Here accumulate not only mechanical rock debris, but samples of everything in the upper several miles of the earth's rocks that will go into solution. Were the ocean waters to evaporate completely, the ocean floors would be covered by a layer of salts and other mineral matter to an average depth of nearly two hundred feet. Here we should find the vanished fertility of our farm lands; sodium and magnesium salts in abundance; gold, thousands of millions of tons of it, silver, copper, nickel in quantities beyond the dreams of avarice—the toll exacted by running or percolating waters upon the upper layers of the lithosphere.

Approximately $3\frac{1}{2}$ per cent of sea water consists of mineral matter in solution. This percentage varies locally, being higher in regions of excessive evaporation, lower in localities having exceptionally heavy rainfall, cold climate, or large additions of fresh water from rivers. Near the equator, where high temperatures are combined with heavy rainfall, concentration of dissolved salts is about average; in the trade-wind belts it is high, falling off north and south to a minimum of less than three per cent in Arctic waters. The principal solid con-

stituents of sea water and their relative quantities are shown in the following table:¹

Salt	Per Cent	Salt	Per Cent
Sodium chloride	77.76	Potassium sulfate	2.46
Magnesium chloride	10.88	Calcium carbonate	.34
Magnesium sulfate	4.74	Magnesium bromide	.22
Calcium sulfate	3.60		

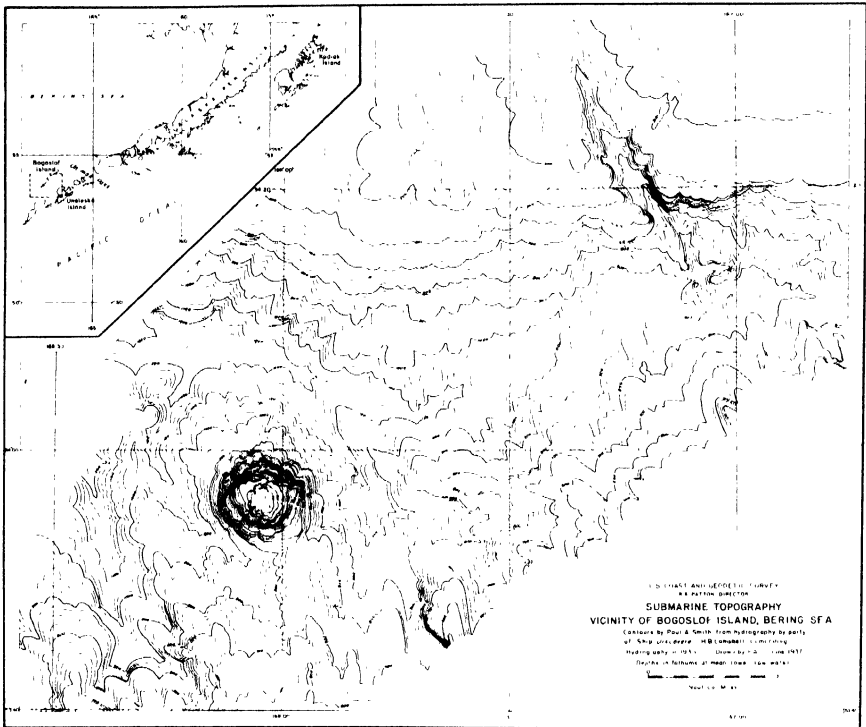
It is quite generally held that all or practically all of the mineral matter present in the sea has been brought to it by inflowing rivers. Upon this assumption, efforts have been made to determine the age of the ocean by dividing the total quantity of a salt or an element that it contains by the annual increment of the same substance; but uncertainties in the fundamental data involved in such calculations are so great that results have little value.

As a matter of fact, there is much reason to doubt that ocean water was fresh to begin with. Its composition differs widely from that of the river water that flows into it. True, calcium carbonate and silica, both comparatively abundant in the water of most rivers, are both removed from the water of the ocean by plants and animals for use in shells and skeletal structures; these and other substances are also at times subject to chemical precipitation. Nevertheless, such scanty evidence as is now at hand suggests that the first water to accumulate upon the surface of the lithosphere may well have been already impregnated with mineral matter absorbed from the primeval atmosphere.

The ordinary gases of the atmosphere, oxygen, nitrogen, and carbon dioxide, are somewhat soluble in water, and all are found in the sea. In part these have been absorbed directly from the atmosphere, in part they have come from volcanic eruptions under the sea, and in part they are the products of the vital activities or the decay of the remains of plants and animals.

Gases dissolve more readily in cold than in warm waters; hence we find more of these substances in polar than in tropical seas. The green color of Arctic waters is due to the presence of great numbers

¹These are the salts obtained by the evaporation of sea water. It should be understood that they do not exist in dilute solution in the quantities indicated. Due to molecular dissociation, the mineral matter present in sea water consists largely of basic and acidic elements or groups of elements known as ions. The figures are from Dittmar, of the *Challenger* expedition.



United States Coast and Geodetic Survey

An underwater Grand Canyon in the Bering Sea. From the side of this mile-deep chasm rises a great volcanic cone; the tiny portion of the summit of this mountain which rises above sea level is Bogoslof Island.

of microscopic organisms, which thrive under the influence of the high gaseous content of the cold water.

Temperatures in the sea. Because of its great heat-holding power and its mobility, sea water is less subject to wide temperature changes than are most parts of the continental surfaces; daily variations may not exceed 1° F. In the tropics the temperature of the open ocean is in the neighborhood of 80° F. A fairly regular decrease occurs north and south, temperatures of polar waters reaching 29° , which is approximately the freezing point of sea water in high latitudes. Arctic waters freeze to a depth of five to ten feet; locally ice may be packed to a considerably greater thickness.

Temperatures drop with depth, rapidly near the surface, more slowly with increasing depth. Below two miles most ocean water is

at a temperature of from 32° to 35° . This coldness is attributed to the sinking of water in the polar regions, and to its slow creep along the bottom toward the tropics.

Density and pressure. Pressure has little effect upon the density of a liquid, which may be considered practically incompressible. The chief factors modifying the density of sea water are its temperature and the quantity of solid matter dissolved in it. At ordinary temperatures the density of ocean water is about 1.027 times that of chemically pure water. Even at a depth of five miles its density is increased only to 1.06.

Pressure, on the other hand, being due to the weight of overlying water, increases steadily with increasing depth. Ordinary atmospheric pressure is doubled at a depth of $33\frac{1}{2}$ feet. William Beebe's bathysphere sustained a pressure of 1300 pounds on each square inch of its surface at the bottom of its 3000-foot descent into the Atlantic, while in the deepest parts of the ocean pressures amount to seven and one-half tons per square inch.

Sea level. The elevations of points upon the continents are indicated with reference to the level of the sea. But this level is theoretical rather than actual; it is a mean or average figure. Not only does the surface of the sea depart somewhat from perfectly spherical form, but its shape changes constantly.

One of the major causes of the more or less permanent distortions of sea level is the gravitational attraction of the land masses. The water is pulled upon by islands and continents, and is thus raised a little higher in their vicinity than out in the open ocean. The water along the Pacific coast is higher than that on the Atlantic side, and the Indian Ocean is believed to stand at a considerably higher level near the western end of India, where it is under the influence of the Himalaya Mountains and other high lands of this vicinity, than farther out at sea.

Of the forces acting to bring about changes in the level of the sea, some are slow-acting and semipermanent, and affect the ocean as a whole, while others alter the level only locally and temporarily. Chief among those of the first class are changes in the topography of the sea bottom, which has probably been affected by occasional sinking

movements throughout much of geological time, although uplifts of the sea floor may occur at times. In the same group should be included the slight rise of the sea produced by the addition of sediments from the land and materials ejected by marine volcanoes. The variations in volume resulting from the withdrawal of water from the oceans in the formation of large glaciers, and the subsequent return of this water to the sea upon the melting of these glaciers, is another factor of considerable importance. Daly reports evidence of a geologically recent general rise of sea level amounting to sixty feet, which he attributes to this cause.

Temporary distortions of the sea surface are brought about by the tides, water entering the sea from rivers or through rainfall, differences in evaporation, differences in density due to varying salinity of the water, and the piling up of water by the winds. Of some importance, if for the mere reason that it is frequently overlooked, is the modification of sea level by changing barometric pressures. Since mercury is thirteen times as heavy as water, a rise or fall of the barometric reading must be reflected inversely in a sea level change thirteen times as great. Changes due to this cause and to alterations in waves, tides, and currents are probably responsible for appreciable fluctuations in sea level that are known to occur, not only from day to day, but over periods which may occupy months or even years, and which may be partly of a periodic nature. Because of alterations of the type just mentioned, observations of the movements of coast lines must be continued over long periods of time to have any validity, and conclusions from them can be drawn only with the utmost caution.

MOVEMENTS OF THE SEA

Waves. When one watches a bit of wood floating in disturbed water, he sees it describe a more or less circular path as each wave passes under it. It rises and moves forward as a wave reaches it, then sinks and slips backward into the trough or "valley" that follows the wave, so that it makes little or no forward progress.

The individual particles of water, in the usual kind of wave, move just about as does the bit of wood; they travel upward and forward, then downward and backward, arriving at approximately their starting points. It is the *form* of the wave itself that moves forward, not

the water of which it consists. If the water moved forward with the wave, sea navigation would be almost impossible, except in the quietest of weather. Waves vary in size from mere ripples to great storm waves 1000 feet or more in length and 30 to 50 feet in height.

The force of a wave diminishes rapidly downward. There is some evidence that sizable pebbles may be shifted about by violent storms at depths of 100 to 200 feet; yet the presence of fine mud on the continental shelf 200 or 300 feet below the surface shows that such depths are as a rule little disturbed by wave action, else this mud would be swept to lower levels. Very exceptional waves do presumably stir fine sediment at a depth of 600 feet. This fact probably constitutes part of the reason that the outer edges of the continental shelves stand in most places at about this same depth.

Waves are produced when the wind blows in irregular gusts, pushing the water up into crests that travel forward, sometimes at the rapid rate of 30 or 40 miles an hour. They often continue long distances beyond the region of their origin. Waves may ultimately die down into quiet risings and sinkings of the water known as *ground swells* or *rollers*.

When a wave approaches a shore over a gently sloping sea bed, the shallowing of the water causes it to rise higher as it progresses. Its front face becomes steeper, its crest bends forward and finally breaks. These waves are termed *breakers*, and collectively constitute the *surf*.

The form of the wave, not the water, moves along.

British Columbia Government Travel Bureau



Small waves break near the shore, larger ones in twenty feet or more of water. After the wave has broken, the water moves in upon the shore.

Ocean currents. The water which rushes upon the shore from the line of breakers usually divides into two currents. One of these returns the water seaward *underneath* the incoming water; this submerged current is known as the *undertow*. Part of the water, however, ordinarily remains at the surface, where it is deflected by wind striking the shore at an oblique angle into a stream which travels parallel to the shore line, and is hence called a *littoral* or *longshore* current.

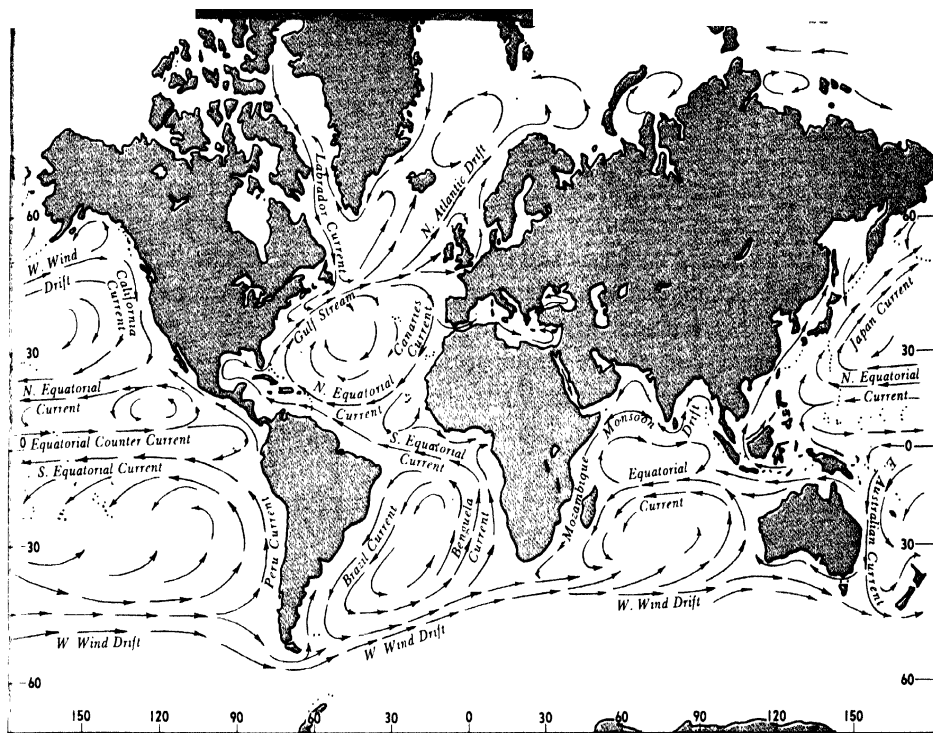
The effects of these small local currents are often easily observable. Tides may also set up shore currents of considerable strength where they enter the mouths of bays or estuaries.

Mention has been made of the sinking of the cold Arctic and Antarctic waters and of their movement along the ocean bottom toward the equatorial regions. In tropical latitudes they rise again to the surface, to join a movement which carries them back again to the polar seas.

Evidence of this circulation is to be found in the fact that animal life exists even in the deepest parts of the ocean, proving that currents of some kind must exist there, since movement of the water is the only medium through which oxygen could be carried to the inhabitants of the depths. Also, basins which are cut off from this bottom circulation do not show a continuous drop in temperature as does the water of the ocean outside of them. For example, the Gulf of Mexico, which is partially shut off from the rest of the ocean by a mountainous wall that rises more than a mile from the sea floor, has below the top of this barrier a constant temperature which is considerably higher than that of the water on the outside at corresponding depths; the explanation of this fact must be that the cold water of the sea bottom cannot creep over the barrier, but moves around it.

The most important of the ocean currents are the surface currents, which are regulated chiefly by steadily blowing winds, especially by the north and south trades.

The trade winds do not blow directly north and south toward the heated equatorial belt, but because of the rotation of the earth are so deflected that the northern trades blow toward the southwest and the



Generalized diagram of the principal ocean currents.

southern toward the northwest. It is these winds that are largely responsible for the westward-moving current in this latitude known as the *Equatorial Drift*. Where this current encounters the continental masses of North and South America it divides, segments turning north and south. In the North Atlantic the north-moving part of the Equatorial Drift enters the Caribbean Sea, then the Gulf of Mexico; here, augmented by the waters of the Mississippi and other rivers, it builds up several inches higher than the level of the open sea and pours out through the Florida Straits at a velocity of three or four miles per hour. It moves northward and eastward, here known as the *Gulf Stream*.

In the vicinity of Newfoundland the Gulf Stream encounters the cold *Labrador Current*, which moves in a southerly direction, keeping in close to the shores of Labrador and the northeastern seaboard states. The heavy fogs common in this region are the result of the confluence of these two currents. As it moves eastward across the Atlantic, the Gulf Stream divides, one segment continuing northeast (the *North Atlantic Drift*) along the coast of Europe, the other bending southward to become again a part of the Equatorial Drift.

Thus the principal feature of the circulation of the North Atlantic will be seen to consist of a great whirl or eddy, rotating in a clockwise direction. A similar eddy exists in the North Pacific Ocean, and others in the South Atlantic and Pacific, both of the latter turning counter-clockwise. These features are pictured diagrammatically on page 217.

Although different types of currents have been described separately, it should be borne in mind that movement of water at any point in the ocean is seldom a simple current, but in all probability the resultant of all sorts of currents, tidal, thermal, or wind-generated, that are acting there at that time.

The tides. Twice each day the waters of the ocean rise and fall. The cause of these tides is the gravitational attraction of the moon, modified somewhat by that of the sun. In the open sea the rise of the water probably amounts to no more than two or three feet, but as it moves upon the shore, especially if the water is forced into a bay or river mouth that narrows to landward, it may pile up much higher. In the Bay of Fundy, for example, the floor of the bay inclines upward as the walls steadily narrow; under these conditions the tidal waters are sometimes heaped up as high as fifty feet.

In places at which the tide enters a narrow inlet and spreads out beyond, its range will be much below that of the sea at the point of entry. In the Mediterranean Sea the water entering the Strait of Gibraltar spreads over so great an area that the level of the Sea is hardly raised at all. The tide in the Gulf of Mexico is rather low for the same reason, amounting to only a foot or two.

Newton's law of gravitation states that the gravitational attraction existing between two bodies varies directly with the masses of the bodies, and inversely as the square of their distance apart. The reason that there are two tides each day is to be found in the relative strength of the moon's gravitation upon (1) the waters on the side of the earth nearest the moon, (2) the solid part of the earth, and (3) the waters that are on the side of the earth opposite the position of the moon. The solid part of the earth acts gravitationally as though its entire mass were concentrated at its center; this section, then, may be considered to be 4000 miles farther from the moon than the waters that are directly beneath that body, and an equal distance *nearer* the moon than those waters on the *opposite* side. Since distance is such an im-

portant factor in determining the strength of gravitational attraction, the water nearest the moon will be pulled up into a high tide; the solid parts of the earth, under less gravitational influence, will be less affected, but will nevertheless be pulled upon more strongly than the more distant waters which, lagging behind the procession, swell into another high tide.

The moon moves around the earth from west to east, completing its circuit in approximately $27\frac{1}{2}$ days. For this reason, it rises fifty-two minutes later each consecutive day, and high tides therefore follow one another at intervals which average twelve hours and twenty-six minutes. High tides do not occur at points precisely beneath and opposite the moon, but lag behind by intervals that differ from place to place. They thus act as a drag or brake upon the earth, slowing down its rate of rotation, gradually increasing the length of the day by an infinitesimal amount, estimated to be about one one-thousandth of a second in a century.

At times of new or full moon, when sun, moon, and earth are nearly in a line with one another, the attraction of the sun is added to that of the moon, with the result that an exceptionally high tide ensues, known as a *spring tide*. This occurs, of course, every two

Waves exert their maximum erosive effect when attacking a bold coast line over water of moderate depth.

British Columbia Government Travel Bureau



weeks. A week after each spring tide the tides are of less than average range, for at such times the sun is pulling at right angles to the direction of the pull of the moon, to some extent offsetting its influence. This subdued tide is called *neap tide*.

The problem of tides is a very complex one, and it should be understood that many of the statements concerning tides apply to average conditions. In some places, for example, only one high tide occurs each day; in others, there are two tides of quite dissimilar character, while in many localities each tide corresponds in every discernible detail to that which precedes or follows. There are also tidal variations from month to month and from year to year, some of which apparently follow a periodic pattern. These tidal inconstancies are due to relations of sun and moon, to the declination of the moon's orbit which causes it to be north of the equator during half its period and south during the remaining half, to varying configurations of coast lines, and perhaps to other factors.

EROSION AND TRANSPORTATION BY THE SEA

Waves as an erosive agent. While of less importance than that of running water, the erosional work accomplished by waves is nevertheless great. The vast amount of water concerned, its relatively high velocity, and the general accessibility of abundant abrasive tools in the form of sand and gravel account for the efficient work of this agent.

The force of ocean waves is sometimes so great that considerable destruction of the shore rocks may be brought about through hydraulic action alone. The average force with which waves beat upon the coast of Scotland has been ascertained to be in excess of 600 pounds per square foot in summer and 2000 pounds in winter. During severe storms the pressure exerted by the waves is known to reach more than three tons per square foot. Rocks weighing 100 tons or more have been moved about by the waves, while at Wick, Scotland, a block of concrete weighing 2600 tons was washed away. Windows in a lighthouse in Scotland 300 feet above sea level are reported to have been broken by stones cast upward by waves, while on an island near the coast of Oregon a block of concrete weighing 1000 pounds was thrown upward 88 feet during a storm.

Another important factor in wave erosion is the hydrostatic pres-



Oregon State Highway Department

Sea cliff and terrace dotted with resistant remnants of the cliff. Oregon.

sure exerted by water forced into crevices or caves. Frequently repeated, this pressure tends to open the cavities more widely, and the total destruction due to this cause is probably far from negligible.

The compression of air by the force of water which completely closes the mouths of sea caves or other openings in shore rocks also causes disruption of rocks, even in places out of reach of the water itself. The walls of the cavities are put under great pressure as the wave comes in; as the water retreats, a partial vacuum may be formed, which also helps to shatter the rocks.

The most effective method of destruction employed by waves is abrasion of the shore by means of rock fragments thrown against it. Under ceaseless attack a rocky coast breaks up, and its disintegration products become weapons for its further destruction. Boulders, gravel, and sand are hurled back against it, fracturing and grinding it away.

The effectiveness of wave action varies with the force of the waves, the character of the shore rocks, the amount and kind of tools available, and with the shape of the shore profile, or cross section. Waves approaching the shore over a gradually shallowing shelf, such as that of the Gulf of Mexico, lose their force through friction with the bottom, and are able to strike but feeble blows against the land. On the other hand, waves moving shoreward through deep water hurl their

full might against the opposing cliffs, but often with but little effect upon the latter, for in such cases any rock fragments present usually lie in such deep water that they cannot be lifted and employed as tools. Other factors being equal, the largest amount of erosive work is to be expected on bold shore lines under attack by waves which move in over a bed of moderate depth, as illustrated on page 219.

As is to be expected from the variety of factors involved in wave erosion, the rate at which shore lines are driven back differs greatly from place to place. Scratches left by glaciers on granite rocks along the coast of Massachusetts have not been obliterated after thousands of years of pounding by the waves. On the other hand, shores built of clay or other soft material are often eaten away with great rapidity. The chalk cliffs of parts of the French and English coasts have suffered extensive erosion during historic times. Parts of the Atlantic coast of the United States have receded 1000 feet or more since colonial days. In places the coast of England retreats at a rate of as much as 14 feet a year, and the sites of a number of villages in this section have been completely consumed by the sea. The island of Helgoland in the North Sea had a circumference of 120 miles in the ninth century; since that time its girth has been reduced to a scant three miles. The island, indeed, would have been destroyed completely by the present time but for the construction of a protective sea wall.

Most sea cliffs show a seaward slope, testifying to the relative efficiency of the weathering processes along the shore.

British Columbia Government Travel Bureau





Canadian National Railways

Cove and headland. Gaspé coast of Quebec.

Sea cliffs and benches. In a shore line which stands for a considerable length of time at the same level, the waves cut a notch, of which the more nearly vertical side constitutes a *sea cliff*. The other segment, which slopes gently seaward, is called a *wave-cut terrace* or *rock bench*. As a cliff is eroded back from the sea, rock debris from its disintegration is shifted this way and that over the terrace, which as a result is ground down to constantly lower levels. This rock material is kept moving until at length it comes to lodge on the seaward side of the bench, in water too deep to permit its easy disturbance by the waves. The structure thus built up of fragmental material beyond the wave-cut terrace is called a *wave-built terrace*.

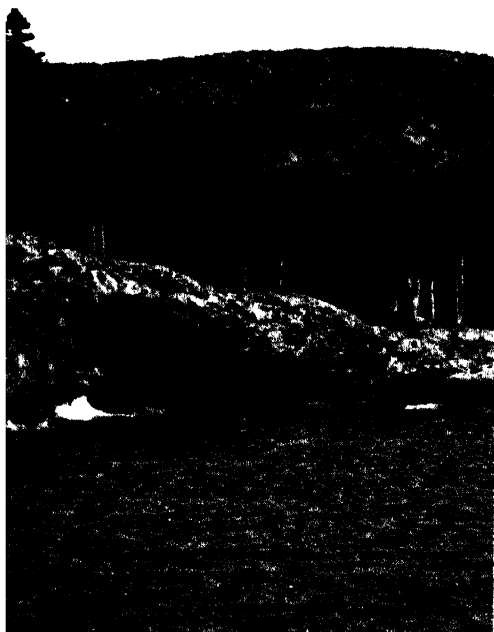
Sea cliffs may be vertical or they may overhang, but a seaward sloping cliff is much the most common type. Weathering along the shore is usually rapid, easily keeping pace with wave erosion, and tending to produce a sloping cliff, like that illustrated on page 222. This is partly because the cliff is kept wet with spray from the sea and with water emerging as springs along its slope, but largely because waves and currents remove material which falls to the base of the cliff, thus preventing the accumulation of a protective mantle of talus.

The shape of a sea cliff is also determined to a large extent by the kind of rock of which it is composed, by the attitude of the rock, and by the presence and positions of joints and bedding planes.

On the Oceanside, California, map (p. 444) may be distinguished at least four different cliffs and terraces, indicating that along this shore the sea has in the past stood at different times at several different levels. The terraces will be found to occur at about 50 to 75 feet, 150 feet, 200 feet, and 300 feet above present sea level, with another possible terrace about 100 feet higher.

As a cliff retreats landward, more and more of the energy of the waves is lost in dragging bottom over the rock bench and the accumulated waste farther out, and in working over the fragmental material cluttering the terraces. For this reason, the width of wave-cut terraces is ordinarily limited. If the shore line happens to be in process of submergence, however, during the process of cliff and bench erosion, the gradual lowering of the bench allows the waves to retain much of their strength to the time they strike against the cliff. Under conditions of submergence, then, it is possible for the waves to drive sea cliffs back for miles, producing broad plains known as *plains of marine abrasion*.

National Park Service



The sea is a maker of caves. Along high, rocky cliffs, waves and currents quickly pick out the less resistant rocks and seams of weakness which they exploit by hurling gravel against the cliffs and by the force of the waves which crash against the shore. Sea caves may be distinguished from those of different origin by the fact that their floors follow an almost horizontal course. Another identifying characteristic is the fact that the entrances of a series of caves along the same stretch of coast will be found to lie very nearly in the same plane, with their floors at about the same level. The cave at the left is on the Maine coast.

Sea caves are common on both the west and the northeast coast of North America. The cave at the right has been driven into basaltic lava on Tanaga Island, in the Aleutians. Wave action has eaten this cave into the cliff for a distance of about 75 feet. It is characteristic of sea caves that they may form in any kind of rock, while the origin of caves due to such agents as chemical solution is generally revealed by the particular kind of rock in which they occur. In the cave illustrated here, the columnar jointing of the basalt was undoubtedly of assistance to the waves in their excavation of the cliff. Sea caves are excellent indicators of former positions of sea level.



United States Geological Survey, photograph by Coats

Minor shore-line irregularities. In the same way that a plateau effects a ragged retreat under the pressure of destructive forces, a shore line will be cut back unevenly by the waves of the sea. Differential erosion produces minor indentations and promontories known respectively as *coves* and *headlands*. Strata of differing hardness which have been tilted in such a way as to present their truncated ends to the sea, localized jointing, or any similar condition might induce more rapid erosion in certain places along the shore than in others. The strength of wave action along a coast may also vary from place to place.

Coves never reach great size, because as they retreat under the attack of the waves they come under the protection of the adjacent headlands. Ultimately a point of equilibrium is reached, after which cove and headland retreat together.

Differences of hardness or exposure also result during the retreat of a shore line in the leaving behind of scattered patches of rock known as *stacks*, which may endure for some time as small islands; several of these are shown in the illustrations on pages 221 and 226. If the waves drive a tunnel entirely through a stack, a sea arch is produced.

Many caves are excavated along bold, rocky shores by wave action, sometimes supplemented by solution. Less resistant spots in the rock, such as those weakened by jointing, are driven back into the cliffs, sometimes for hundreds of feet or even in exceptional cases for half a mile or more. All forms of wave erosion are employed in the formation of sea caves, the action of compressed air being relatively important, since the shoreward ends of these cavities are protected from the full hydraulic and abrasive force of the waves.

Since sea caves are developed only at the shore line, their presence is reliable evidence of former positions of sea level. Many good examples of sea caves, both recent and ancient, are to be found along the New England, Labradorean, and Pacific coasts. Two such examples are shown in the illustrations on pages 224 and 225.

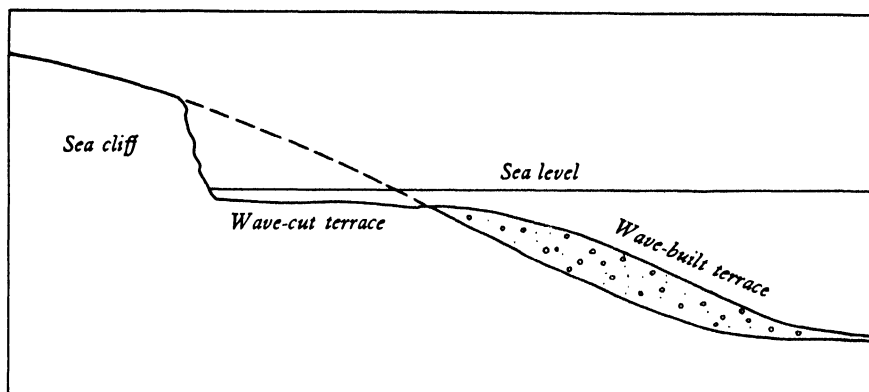
If the landward end of a sea cave emerges at the surface, or if the cave encounters a crack which does so, water may be thrown out through the opening during heavy weather, while at calmer periods air may move in and out as waves enter and recede from the seaward end of the cave. An opening of this kind is known as a *blowhole*, or spouting horn.

Under conditions of very rapid marine erosion, hanging valleys may be developed in the beds of streams flowing into the sea. The chalk cliffs of France are being cut back so rapidly by wave action

Stacks along the rocky shore of Georgian Bay, Ontario.

Canadian National Railways





Relations of sea cliff, wave-cut terrace, and wave-built terrace.

that rivers flowing over their edges are unable to deepen their mouths to sea level, and hence constitute hanging valleys.

Erosive effects of currents. The erosive effects of the major ocean currents are as a rule negligible. The movement of the water is too slow to permit any important direct effect upon the lithosphere, or the movement of abrasive materials. In a few places constriction of the paths of large currents may increase the rate of movement sufficiently to produce some erosion of the bottom, even in water that is quite deep.

Locally, shore currents of one kind or another may do considerable erosive work. The undertow, for example, is capable of dislodging loose materials from their positions in shallow water. The tides too may develop rapid currents when the water is forced into constricted areas. If two bays or estuaries are connected by a channel, and if the tide reaches a higher level in one than in the other, a tidal race will flow from the former to the latter during flood tide, and in the reverse direction during ebb tide. The race in Hell Gate is due in part to this cause.

Transportation. Transportation of solid matter by the sea is limited practically to a narrow band of shallow water near the shores. The general ocean currents are of very little importance as a transportation agent, except in unusual situations in which their velocity is greatly increased by passage through narrow straits. It is the currents generated in connection with waves in the shallow waters that effect the

movement of the great bulk of sediment brought to the ocean by rivers or torn from the shore rocks by the waves.

In this region of shallow water, waves are constantly disturbing materials lying on the bottom. But since the water in a wave does not ordinarily move forward, waves acting alone cannot serve as agents of transportation. Currents, on the other hand, move sediment forward with them, but are usually too feeble to raise material from the bottom. It is when waves and currents interact that shallow-lying material is picked up and moved about. Since currents cannot long sustain mineral fragments in suspension, the latter are dropped after only a short journey, to await the lifting effect of the next wave; rock waste thus travels along the shore by discontinuous stages.

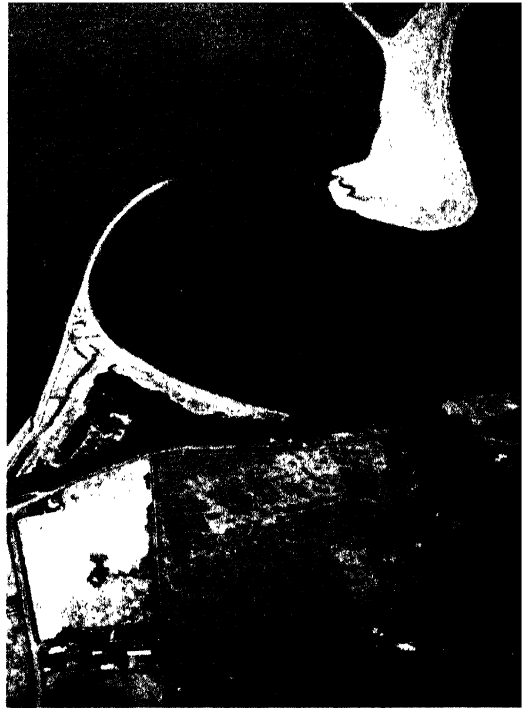
Since lighter fragments are moved more easily than heavier ones, wave and current action tends to bring about a sorting and separation of various kinds of migrating material. The coarser particles eventually reach depths at which they can be but little disturbed by the waves, which can still raise the smaller pieces. A similar sorting action results from the way water acts upon reaching the shore. Breaking waves hurl their water landward, carrying along particles of all sizes. At the shore line this water, as has been previously noted, forms two streams, the undertow and the longshore current. Each of the latter are weaker than the incoming current which produced them; large rock fragments cast upon the shore are therefore likely to remain, while lesser particles are returned seaward by undertow and longshore current.

Daytona Beach, Florida. This beach is built of sand brought from the southern Appalachians, far to the north.

Florida News and Photograph Service



In the partly protected waters of the Strait of Juan de Fuca, between Washington and Vancouver, the sea strives to drop some of the sand which it has received from inflowing rivers, or which its waves have torn from nearby shores. Here we see a narrow spit of sand building seaward across the channel, while a more massive sandbar extends toward it from the opposite direction. The sea currents, evident in the curving shape of the spit and in the small, swept-back projection of the larger sandbar, will probably prevent the accumulating sand from closing the mouth of the strait. The rapid current, sweeping past the spit, deposits less sand than the quieter waters near the larger sandbar.



Beach Erosion Board, War Department

MARINE DEPOSITS

Origin and characteristics. By far the greatest part of the sediments laid down in the sea is that which has been derived from the mechanical wasting of the continents. These deposits contrast sharply with those laid down upon the land. They lack the variability of structure, color, and content often so conspicuously displayed by continental deposits. They are also lacking in raindrop impressions, mud cracks, and other evidences of exposure to the atmosphere, but ripple marks may be present. The latter, if produced by ocean currents, are of asymmetrical shape, in this particular resembling those made by wind or fresh water; some marine ripple marks, however, have symmetrical outlines, indicating that their origin was connected with wave action rather than with currents. Sea muds may be gray, blue, black, or green, but are almost never red except in the great depths and near the mouths of some tropical rivers.

Beaches and bars. Except along shores bordered by exceptionally deep water, rock fragments torn from the shore in the cutting of cliffs and terraces, together with debris brought to the sea by rivers, form a

continuous sheet of migrating drift adjacent to the shore. On the whole, this material is traveling toward deeper water, where it at length comes to rest as a *wave-built terrace*, bordering the wave-cut terrace or rock bench on the seaward side as shown in the diagram on page 227. But for a time following its entrance into the sea these mechanical sediments are tossed and rolled about in the shallow water, making temporary stops which in some cases take the form of special types of deposits.

Year upon year, along unprotected sweeps of coast, littoral currents drive the longshore drift in a never-ending stream. The part which lies above the low-tide limit is termed the *beach*. Beaches are frequently formed in sheltered areas such as the heads of bays (*bay-head beaches*), where they may be washed up above the normal limits of the tides. A beach is most commonly made up of quartz sand, usually rather well sorted; it may, however, consist of boulders or, in exceptional situations, of mud. A shingle beach is one consisting of rocks measuring several inches in diameter. The term is usually applied

A mass of accumulating sand builds up into a bar off Nantucket Island. Note the regular seaward face, the dentate inner margin.

Beach Erosion Board, War Department



to a beach of overlapping, flattened boulders, the shape of which is probably in most cases connected with the structure of the rocks from which they originated. Beaches of coral sand or other unusual substances occur in rarer instances.

During the active dissection of a coast line or of the hinterlands contributing sediments to a coast, the supply of sand may become so excessive that some of it is deposited in the form of islands, or built out in various forms from the land. Points of sand projecting into the sea are termed *spits* (see illustration, p. 229); these are of especially common occurrence at the mouths of bays, where shore drift is washed into deeper water. In an instance of this kind, more sand is carried over the top of that already laid down, and is dropped at the further end; if this continues until the deposit closes the mouth of the bay, as it has nearly done in the case illustrated on page 232, the structure constitutes a *bay bar*. When spits and bars have been built up close to the water level, strong waves may throw some of the sand above the surface. In this case, or even as a result of exposure to the air during low tides, surface sand may dry out sufficiently to be heaped up into dunes by the wind. In this way these deposits may come to have elevations of several feet above sea level.

The Tamalpais, California, map (p. 448) shows a bar of this type almost closing the mouth of Bolinas Bay.

In the course of their construction bars may encounter transverse currents, or they may be attacked by waves on one side, with accompanying deposition on the other. A bar pursuing a curving path as a result of such influences is called a *hook*. A strip of drift so deposited that it connects a small island with the mainland is a *tombolo*.

Along low, shelving coasts, such as those which have recently undergone uplift, large waves break at a considerable distance from shore, perhaps several miles. These waves scour the bottom over which they move, and deposit quantities of sand along the breaker line. Sand is also brought down to this line by the undertow, and further additions are undoubtedly made by longshore currents. There results from this deposition a long, narrow island, lying parallel to the shore; an island so constructed is known as an *offshore bar* or *barrier*. It may lie at a distance of a mile or more from the shore, from which it is separated by a *lagoon*. One or more smaller offshore bars may lie within the lagoon, built up by weaker waves.

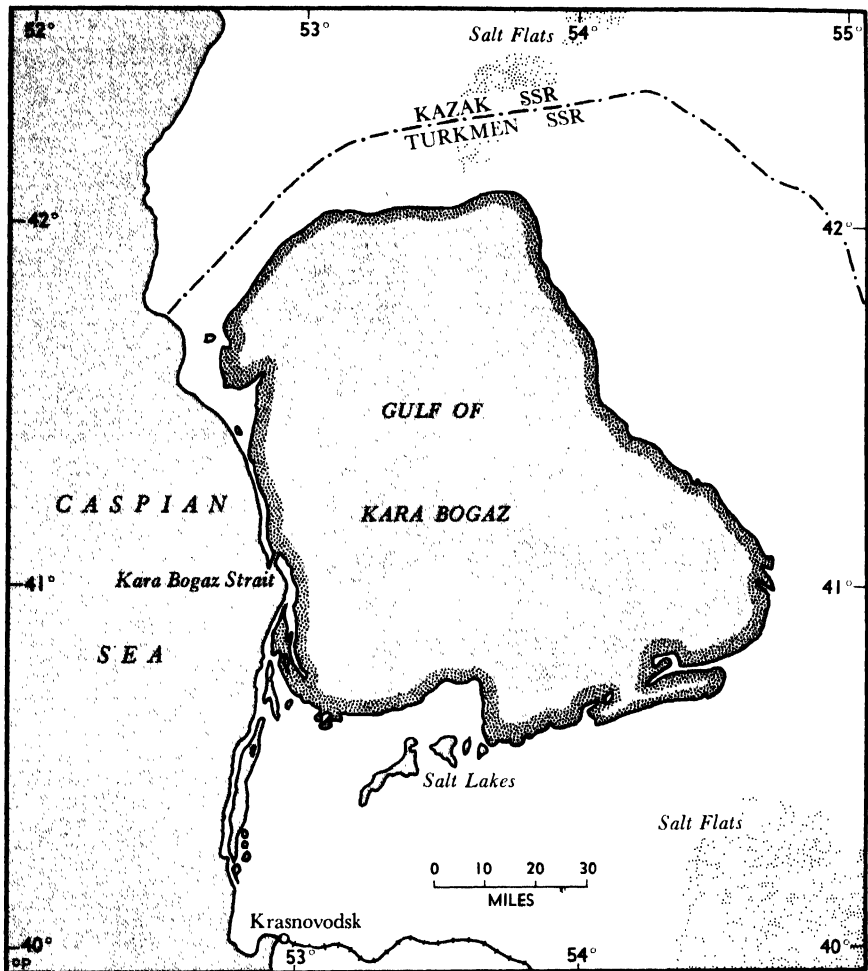
Deposits made in lagoons along the seashore present a mixed picture of continental and marine conditions. Clastic sediments from the land may be deposited in the form of river deltas or spread out over the bottom of the lagoon, the relative quietness of the water favoring a rapid gradation in fineness away from shore. Sand washed inward over or through gaps in the seaward bar is deposited along the inner margin of the bar, or as a series of deltas. Under certain conditions salts may be laid down in lagoons. Mechanical sediments grade laterally into swamp deposits, as a result of the shallowing and filling of the lagoon and the establishment of vegetation along its margins. Fossils will represent both fresh-water and marine environments.

If the evaporation of water from a lagoon is very rapid, concentration of salts within it may reach a very high point, since water containing dissolved solids is constantly entering the lagoon from the lake or ocean with which it is connected. Ultimately deposition, usually of calcium carbonate or gypsum, takes place. The lagoon may be cut off entirely from the parent body, and become a saline. Very thick deposits of salt, gypsum, or similar soluble substances are believed to have had their origin under some such conditions as these. Among these deposits is one at Stassfurt, Germany, where beds nearly a mile

Sand deposits become part of the mainland of Connecticut, while a lengthening bar seeks to cut off an estuary from the sea.

Beach Erosion Board, War Department

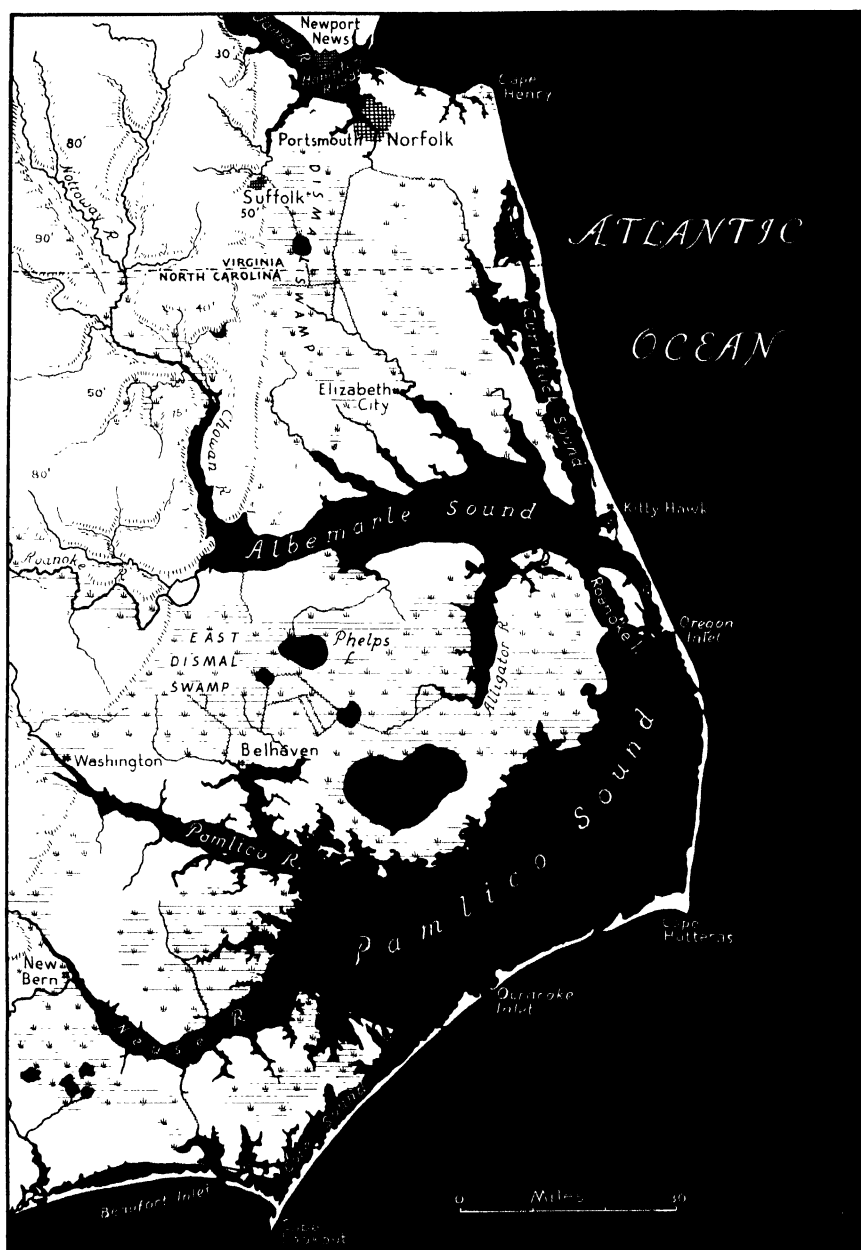




The salty water of the Caspian Sea, drawn into Kara Bogaz Gulf by the rapid evaporation occurring there, becomes so concentrated that precipitation of some of its dissolved solids takes place.

thick furnish supplies of salt and potash. Similar deposits are located in Russia and in west Texas and New Mexico. Extensive beds of salt also occur in New York, Ohio, Michigan, and Kansas.

One of the best illustrations of the conditions leading to the deposition of dissolved salts in lagoons is to be found in the Kara Bogaz Gulf, located in a semidesert district on the east side of the Caspian Sea. As can be seen from the picture on this page, the gulf is sepa-



A section of the Atlantic coast showing offshore bars, lagoons, and coastal-plain swamps. Dismal Swamp is situated in an almost flat region between the sea and an ancient sea cliff.

rated from the Caspian by a very narrow inlet which is partly choked by sand deposits. Evaporation from the surface of the water of the gulf is so rapid that a steady current is drawn in through this inlet. The concentration of salts in Kara Bogaz Gulf, therefore, is much greater than in the Caspian—so great, in fact, that some of the less soluble materials are precipitated.

An offshore bar is not continuous along the coast, but is interrupted by occasional tidal inlets. The spacing of these openings is determined by the range of the tides and probably also by the supply of available sand. Tidal currents entering and leaving the lagoon through these inlets frequently deposit deltas on both seaward and landward sides.

Offshore bars are well developed along the Atlantic and Gulf coasts of the United States from New Jersey southward. A part of one such bar is shown on the Ocean City, Maryland-Delaware, map (p. 443). Note the straight seaward margin of this bar, and the irregular landward face. Small sand dunes dot the surface of the bar, showing that the wind was instrumental in increasing its elevation above sea level. We see on this map also the swamps forming along both the bar and the mainland, pointing toward the ultimate disappearance of the lagoon. Compare the features noted on this map with those observable in the photographs on pages 229, 230, and 232.

Offshore deposits. By far the largest part of the sediments which are accumulating today is being deposited upon the continental shelves, 10,000,000 square miles or more in extent, the upper parts of the continental slopes, and in the two large inland or epeiric seas, the Baltic and Hudson Bay. Deposition in these regions is brought about chiefly through three processes: (1) retardation of currents of water, (2) flocculation, or the association of very fine sediment into small lumps, and (3) the activities of organic agents. In addition, a minor amount of deposition results from chemical processes.

The various movements of ocean waters are quite effective in the sorting of rock fragments of all except the smallest sizes. Waves, currents, undertow, tides, all co-operate in shifting sediment about, moving especially the lighter particles; ultimately the coarser pieces find lodgment in situations from which they are not thereafter disturbed, while the finer material is lifted from among them, to be swept up

and down the coast line until it also is dropped in water too deep to permit further disturbance by the waves.

If a shore is high and rocky, gravel will be present in the shore drift, and will be laid in relatively shallow water, usually no more than fifty or sixty feet in depth, although rounded pebbles may be rolled much farther out. Sand will extend, in most regions, into water some 300 feet deep, where it grades into a dark-blue mud. This mud continues up to and beyond the edges of the continental shelves, extending downward over the continental slopes to depths of three miles; it covers a vast area, approximating 15,000,000 square miles. Comparatively small areas of green and red muds are also known.

Limited areas of black muds occur on the continental shelves, usually in partially enclosed basins, or in depressions in the sea bottom. Black muds contain disseminated carbonaceous matter, and their presence indicates poor circulation of water; they are formed in places in which acids accumulate, preventing the normal destruction of the organic material which becomes embedded in them.

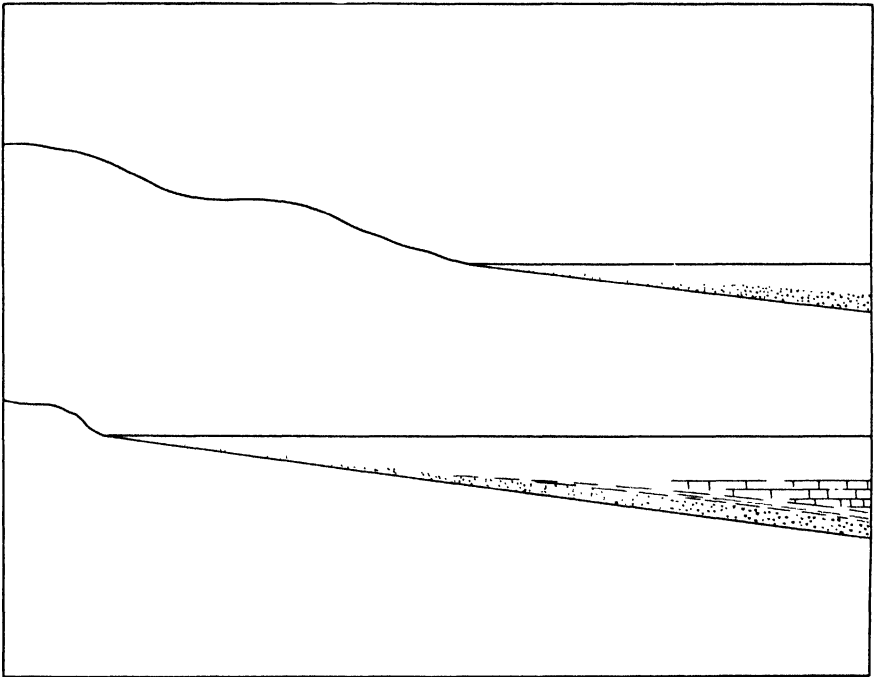
In general, the clastic sediments deposited through mechanical means are distributed in such a manner that the coarsest materials are nearest shore, the finer arranged in the order of decreasing size of particles seaward. Locally, however, the distribution of sediments is very irregular, and in some cases the order of distribution is just the reverse of that normally obtaining.

The extremely small colloidal particles of clay are unresponsive to changes in the velocity of the water, on account of their relatively large surface area, which offers strong resistance to settling. These particles are kept separated in fresh water by electrical repulsion, since they carry minute charges of similar kind. Upon entering sea water, these charges are ordinarily neutralized by opposite ones carried by dissolved salts, permitting the clay particles to flocculate or clump together, forming masses of greater weight and relatively smaller surface area, which readily settle to the bottom.

In addition to clay particles, beds of silica are sometimes deposited in this same manner. These silica beds are of limited extent, and often of rounded shape; they appear to have been formed in most cases near the mouths of rivers, where intermingling of fresh and salt waters took place, although some are formed at some distance from shore, prob-

ably as a result of the overriding of sea water by the lighter river water, which was carried seaward for a time before losing its identity.

Organic agents are responsible, directly or indirectly, for the deposition of most limestones. Among the most important sources of this rock are the so-called coral islands. Some of these islands form almost in contact with the shore, and are consequently known as *fringing reefs*. Others, *barrier reefs*, are found in deeper water, usually in the form of islands parallel to the shore. Still other forms, also at some distance from the shore, are *atolls*, ring-shaped structures enclosing lagoons. Corals take calcium carbonate out of the water in which they live, building it into protective shells, which remain as parts of the reef after the death of the animals. In a "coral" reef, corals are not the only, or necessarily even the most important, lime-secreting organisms; algae, which are primitive plants, single-celled animal forms known as foraminifera, and a number of other organisms often contribute more limestone to the deposit than do the corals themselves. For this reason, the term *bioherm* is coming into use to denote such



Subsidence of a coast line results in the deposition of sediments which become progressively finer upward.

a plant and animal association, in preference to the expression *coral reef*.

Corals and most other limestone-forming organisms require clear sea water; hence limestone from such sources often forms in moderately deep water at some little distance from the shore, and is generally unassociated with muds. In protected places, however, fringing reefs may develop in shallow quiet water. Colonial corals appear unable to survive at depths greater than 150 feet, or in water colder than 68° F.; in addition, although the water in which they flourish must be clear, it must have moderate currents, to bring in food and oxygen.

Plants, as already noted in connection with river deposits, cause deposition of calcium carbonate either by the direct removal of carbon dioxide from the water for use in their photosynthetic processes or by its extraction from the soluble calcium bicarbonate, with the consequent reduction of the latter to calcium carbonate, which cannot remain in solution. Agitation of the water leading to expulsion of carbon dioxide may also result in limestone formation, although this cause is relatively of little significance in marine deposition.

Grinding and pounding by waves reduces large quantities of limy shells and bones to a fine powder. This material, together with that arising from the destruction of pre-existing limestones, may be laid down mechanically in deep water, exhibiting the usual marks of clastic sediments, such as ripple marks and cross-bedding.

Generally speaking, deposits of limestone are to be interpreted as indicative of water deeper than that in which mud is ordinarily laid. It must be borne in mind that this does not preclude the possibility of deposition in shallow water, if it is sufficiently clear.

Among the minor constituents of the accumulating sediments around the shores is glauconite, a greenish silicate of iron, which may be encountered from shallow waters down to depths of more than a mile. Glauconite is usually associated with sand, to which the name *greensand* is applied, or with some limestones. Its origin is unknown.

When deposited, most strata are almost horizontal, although never exactly so. In some cases they may be formed upon surfaces which are inclined at a high angle; they will remain in such a position, however, only if the water or air which covers them is relatively quiet. Almost all strata are lenticular in shape, pinching out at their edges,

and intertonguing with overlying and underlying layers. In many cases also a stratum gradually changes in character from one place to another; a limestone, for example, may become more and more shaly until it eventually assumes the composition and other characteristics typical of a pure shale.

Since it is the general rule that the coarser sediments are laid near shore in shallow water, muds farther out, and limestones out of reach of most of the mud, it is evident that either a rising or a sinking movement affecting the coast line will bring about an alteration in the relations of the accumulating sediments. If, for example, the coast is subsiding, the encroaching sea will lay finer sediments in the gradually deepening water offshore, above the coarse materials which had been laid when the water was shallow. Thus a succession upward of sandstone, shale, and limestone, the finer sediments overlapping the coarser shoreward, indicates subsidence; these conditions are shown in the diagram on page 237. If the base of such a section represents shore conditions, it may consist of a layer of consolidated gravel known as a *basal conglomerate*. If, on the other hand, limestone is overlain by shale, indicating that the depositing waters were becoming muddy, or if shale is covered by sand, the section may be interpreted as evidence of a rising coast line.

Marine shales and limestones are the richest of all sources of fossils. These limestones may consist of the shells of many kinds of sea animals, the bones of fish, and a few other forms.

The importance to the geologist of the stratified form in which many sedimentary rocks exist can hardly be overstated. In undisturbed strata it is evident that the layer on the bottom of the series is the oldest, and that the overlying layers are progressively younger. This rule of superposition, used in combination with the correlation of strata by means of their included fossils, forms the foundation of geological chronology, which has brought a high degree of order into the formerly chaotic realm of earth history. Upon the systematic classification and mapping of strata have been built the science of oil prospecting and other geologic procedures of incalculable value to man.

The term *formation*, while employed by geologists in a number of different senses, generally signifies a group of successive strata formed under more or less uniform conditions, which may be conveniently treated as a unit. A formation may consist of rock chiefly of one kind,

or it may include layers of different kinds; in any case, all the strata were formed without any important interruption of the process of sedimentation. A formation usually receives a name derived from the locality in which it was first identified and studied.

Intermediate and deep-sea deposits. On the surface of the ocean floats the plankton, an assemblage of countless numbers of microscopic plants and animals. Many of these possess shells of lime or silica. Upon the death of the organism, or its desertion of its shell, the shell slowly settles toward the bottom. This occurs everywhere in the ocean; but near shore the accumulation of tiny shells is masked by the far more abundant mechanical waste from the land. Where the fine mud begins to thin out on the continental slopes, however, these shells, together with those of other minute forms which dwell on the bottom, form a white, chalky ooze, which is chiefly calcium carbonate in composition.

The quantity of calcium carbonate decreases gradually with depth to a level of about 13,000 feet, below which it diminishes rapidly. At a depth of three miles it has practically disappeared, due, apparently, to the solution of the shells as they encounter water which is under great pressure and which is also impregnated with carbon dioxide. Both of these factors increase the solvent power of the water, but they do not seem entirely adequate to explain the suddenness with which the limy ooze comes to an end.

Some contribution may be made to this limy ooze by chemical precipitation. Where currents of water are rising toward the surface, as in the region of the equator, decrease in hydrostatic pressure, as well as loss of carbon dioxide resulting from increased temperature, may cause precipitation of lime. Most lime so precipitated would be re-dissolved upon settling into the depths, although some might find lodgment on shallower bottoms.

Below a depth of three miles, most of the sea floor is carpeted by a fine red clay, which is accumulating so slowly that the bones of sea animals extinct for thousands of years still lie upon its surface. This clay appears to consist in large part of materials ejected from volcanoes, to which are added wind-blown dust, insoluble parts of the microscopic shells, and the dust from meteors consumed in the atmosphere. The red clay covers an immense area of the sea bottom, especially in the

Pacific; its extent is in excess of 50,000,000 square miles, or the equivalent of all the land surfaces of the world. In places it gives way to a chocolate-colored clay, and in some of the deepest parts of the ocean, to an ooze consisting of a mixture of clay and microscopic shells of silica.

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XI · DEFORMATION OF THE ROCKS



In previous chapters it has been pointed out how rocks are formed, and attention has been directed to some of the structural features which sedimentary rocks possess by virtue of the special conditions of their deposition. The stratification planes which are present in most sedimentary rocks serve as reference planes by which we may determine what change in attitude or position such rocks have suffered. It is usually assumed that all beds of rock are initially deposited in an approximately horizontal position and that they are fairly continuous in extent and uniform in thickness. Such an assumption as pointed out in a foregoing chapter is not justified. Although many sediments maintain a remarkably uniform thickness over great distances, they are always broadly lens-shaped, and conform to the inclination of the surface upon which they were laid. Furthermore, the coarser sediments are rarely carried in suspension, but instead are rolled or dragged along until the velocity of the transporting agency is checked. The actual original position of a sedimentary deposit is therefore determined largely by the slope of the floor upon which it is laid down, provided the slopes of this floor are not steep enough to permit slumping of such material.

ADJUSTMENT TO ENVIRONMENT

As soon as sediments are deposited they immediately become subject to changes. These changes include consolidation by the weight of overlying material and cementation through material deposited or chemically precipitated around the grains. Some sediments such as wet clay may thereby lose more than half of their volume through compacting and the resulting exclusion of water originally deposited with the clay particles.

Other changes occur through lateral and vertical compression originating in earth movements which are commonly called *diastrophism*. The origin of such earth movements is somewhat obscure, although

Jointing in the Fayetteville formation of Mayes County, Oklahoma. Joints in sedimentary rocks may be the result of drying out, or of the stresses developed during the warping of the earth's crust. Joints, which often tend to occur in parallel series, together with bedding planes, frequently break massive limestone up into neatly piled, square blocks.



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geologists generally recognize that two major causes are responsible: first, the tendency of the denser portions of the earth to sink and thereby squeeze the lighter segments between them; and second, the liquefaction of some areas within the earth, which permits the resulting molten material to move to areas of less pressure. This latter process gives rise to volcanic phenomena which commonly accompany mountain-making and other profound diastrophic movements. Throughout all of geologic time the earth has been subjected to almost continuous movements of readjustment. At certain periods these movements have taken the form of widespread revolution affecting simultaneously many different continents and causing great series of mountain uplifts.

The effect of these minor and major earth movements on the rocks themselves is usually referred to as *folding* and *faulting*. If the original position of the layers of bedrock has been changed but the bed is still continuous, it is said to have been *folded*. If an actual break occurs and there is displacement along the plane of the fracture surface, it is referred to as a *fault*. Frequently faults and folds occur together or pass into each other vertically or laterally. Some rocks break much more easily than others when subjected to deforming stresses. Shales and similar thin-bedded sediments often yield to such stresses by thickening, thinning, or folding, instead of breaking. Such rocks are referred to as *incompetent*. Thick beds of limestone or sandstone are usually capable of transmitting a stress without suffering interior deformation, and are referred to as *competent* rocks.

Rock flowage. When rock is subjected to more stress than it can withstand, it may respond in either of two ways; it may *crack* and slip into positions of lessened pressure, or it may *flow* into an altered form without visible signs of fracture. This latter process is somewhat analogous to the plasticity exhibited by wet clay; under certain conditions, however, even the most hard and brittle rocks can be made to flow. This phenomenon has been observed in deep mines and tunnels, and in the laboratory. Further graphic evidence of it is to be found in the banded or distorted condition of the constituents of many metamorphosed rocks.

Rock flowage results from a rearrangement of the particles of the rock brought about by slippage along microscopic surfaces of grains or crystals, by altered positions of the molecules themselves, or by the reorganization of the rock constituents into new minerals. The ease with which any rock will flow depends principally upon the nature

This almost vertical cliff is the result of weathering along a large joint in the red sandstone of Canyon de Chelly, Arizona. Rapid weathering in a less resistant region produced the cavern near the center of the picture. The parallel streaks on the face of the cliff are discolorations produced by iron and manganese oxides deposited by water coming from above.

National Park Service, photograph by George A. Grant



Closely spaced joints in rhyolite flows of Chiricahua National Monument, southeastern Arizona, result in the sculpture of many odd forms. The joints make the rock unable to withstand the effects of water and air erosion and promote very deep-seated weathering, often with the startling results shown in this illustration. In igneous rocks, joints frequently result from contraction caused by cooling. These joints may take various forms, depending upon the size and shape of the igneous mass, the rate at which the cooling proceeds, and other factors. One of the most striking results of this process is the production of columnar jointing, in which the cooling rock contracts into regularly shaped columns.



National Park Service, photograph by George A. Grant

of the rock, the amount of pressure it is under, the rate at which the pressure is applied, the way it is distributed around the rock, and the time during which it is effective. High temperatures and the presence of moisture facilitate flowage in most instances.

The depth at which rocks will flow is still largely a matter of conjecture. The strongest rocks are crushed under a pressure slightly exceeding 30,000 pounds per square inch. If it is assumed that rock supported on all sides by a confining pressure will flow upon the application of pressures exceeding its crushing strength, flowage of all rocks would be expected at depths of three to five miles. Compression, however, increases the strength of a rock, by forcing its molecules into closer proximity. Adams and King bored .05-inch holes in granite cylinders, which were then subjected to pressures of 96,000 pounds per square inch, equivalent to the pressure which exists at a depth of 15 miles; yet no change was observed in the size of the openings. Present indications are that the strongest rocks may not flow at depths less than thirty miles.

Rock fracture. Rocks may fracture with or without any evident displacement. Fracturing may result from stresses set up by the cooling of heated rocks, by the shrinkage of sediments upon compaction, or from the effects of diastrophic movements.

Joints, or cracks unaccompanied by displacement parallel to the plane of the fracture, may result from tensional (stretching), compressional (squeezing), or torsional (twisting) stresses, and they frequently occur in sets or systems, characterized by a parallelism of the fractures. Joints due to shrinkage may assume the very distinctive pattern exhibited by those resulting from cooling of a mass of basalt, as shown in the illustrations on pages 245, 320, and 325.

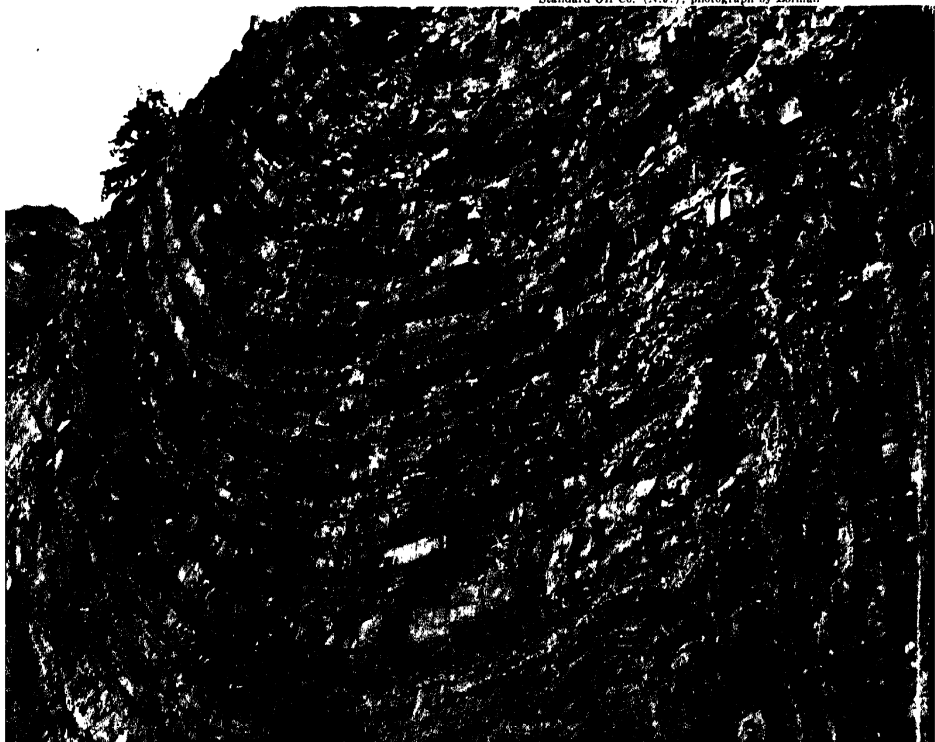
Great compressional stress tends to develop two sets of joints nearly at right angles to each other and at a 45° angle to the direction of maximum compression. Tensional stress develops fractures at right angles to the direction of greatest stress.

The direction of maximum compression is the direction of minimum tension and vice versa. Therefore we find both tensional and compressional fractures developed in the same mass of rocks.

When joints are well developed, rocks appear to have been sliced

Folding of incompetent beds. Near Atoka, Oklahoma.

Standard Oil Co. (N.J.), photograph by Lofman



vertically into a series of blocks by a gigantic knife (see page 243). When such rocks are subjected to normal agencies of weathering and erosion, the joints usually are visible as the surfaces along which the rock is exposed in columns, buttresses, and cliffs. It is these joints which make it possible to quarry blocks of rock with rectangular outlines instead of with jagged, irregular surfaces. The illustrations on pages 244 and 245 show some of the diverse effects of weathering along joint planes.

Wherever a thick section of shale rocks occurs there will usually be found well-developed joint planes, and the lack of resistance of such rocks to erosional forces generally overemphasizes the effect of jointing by making it very conspicuous. In limestone and sandstone areas many of the joint planes are not evident; here they generally do not exist as open fissures, and are called "blind" joints.

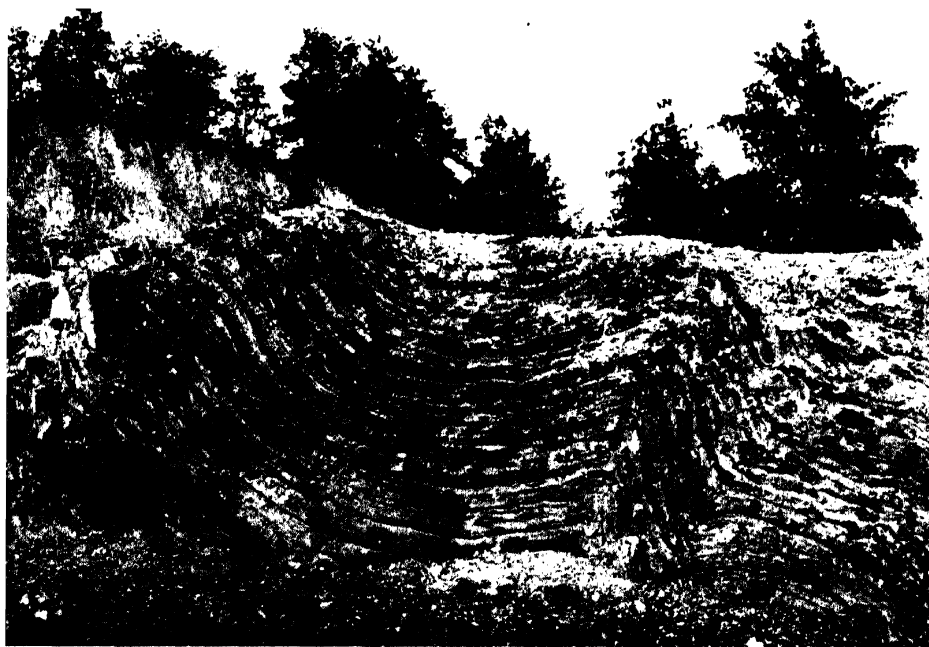
ROCK FOLDS

Causes of folding. Folds in rocks (pp. 246 and 248) may result from either fracture or flow. Suppose a stratum of limestone is broken by vertical joints into a large number of blocks. Pressure exerted upon these segments forces them to slip out of position, those in one section moving upward, those at some distance being depressed. The stratum is thus deformed, and the cracks along which displacement occurred may later be filled with limestone, leaving little or no indication of their existence.

Deeper in the earth, under very heavy lateral pressures and very heavy load, strata are deformed by flowage. Folds due to this cause are often much more complex and intricate in detail than those produced by fracturing and slipping.

Of course all types of rocks are subjected to the same stresses within the earth, and therefore igneous and metamorphic rocks are folded and faulted just as much as the sedimentary rocks. When we use the term *fold* or *fault* we usually refer to sedimentary-rock relationships, because it is only in the stratified rocks that the handy reference surfaces we call bedding planes exist. Without such surfaces we have no method of determining the nature and extent of the deformation.

Terminology of folds. If a layer of rock was not deposited in a horizontal position it is said to have an *initial dip*. Although under



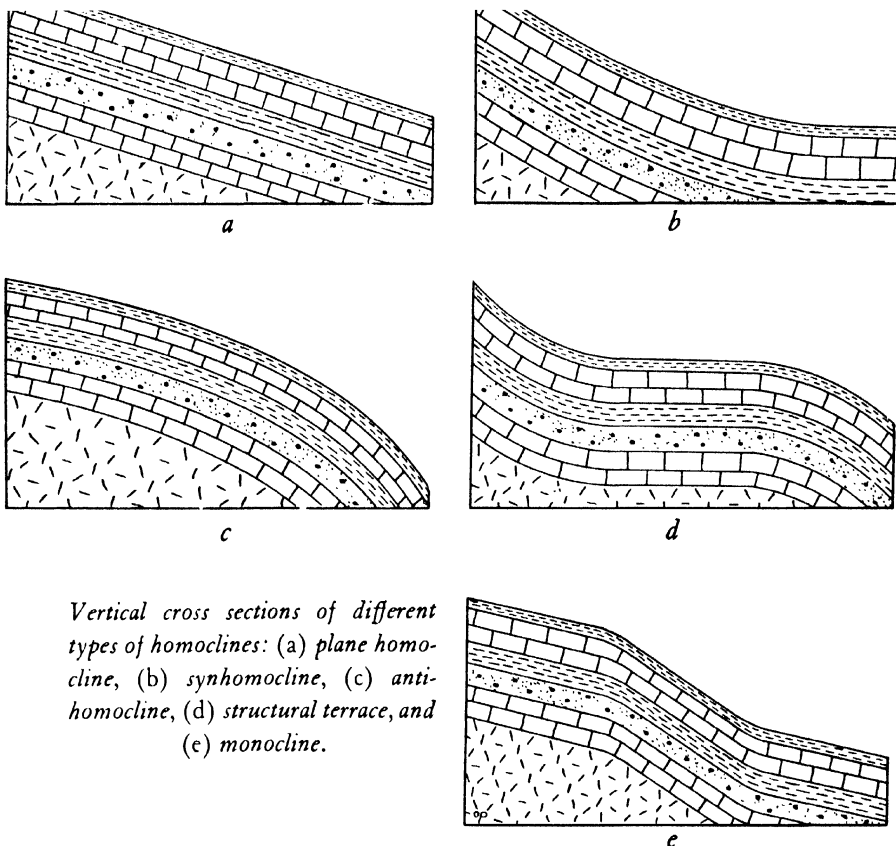
Standard Oil Co. (N.J.), photograph by Lofman

Folding as seen in road cut. Near Atoka, Oklahoma.

Homoclinal dip in sandstone. Near Warren, Montana.

Standard Oil Co. (N.J.), photograph by Rosskam





Vertical cross sections of different types of homoclines: (a) plane homocline, (b) synhomocline, (c) antihomocline, (d) structural terrace, and (e) monocline.

favorable conditions it is possible for this initial dip to be as much as 25° , we rarely assume dips to be original if they are more than 2° or 3° from the horizontal.

When a bed of rock has had its original position altered, it may assume any of the following attitudes: (1) it may, very rarely, be horizontal or level; (2) it may be inclined so that it dips in one general direction; (3) it may dip in two opposite directions; or (4) it may dip in all directions. These folds may be referred to as (1) aclines, (2) homoclines, (3) anticlines and synclines, and (4) domes and structural basins.

It must be realized at the outset that these are structural terms and do not refer to the topography. Actually a dome structure of the rocks may be overlain by a lake basin at the surface of the ground. The Grand Canyon is a mile-deep surface feature, but the rocks into which it is cut are nearly flat.

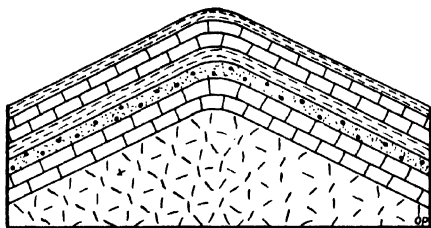
When an inclined bed of rock intersects a level surface of land, the direction of the resulting *outcrop* is referred to as the *strike* of the rock at that place. In other words, the strike of a rock is the direction of the intersection of a bedding plane with any horizontal plane. It is therefore the line standing water would make on a dipping bed.

The strike of a rock is always recorded as a certain number of degrees east of north or west of north. Therefore a bed striking N. 45° E. would run at right angles to a bed whose strike was N. 45° W. A bed whose strike is N. 89° W. would be almost east and west.

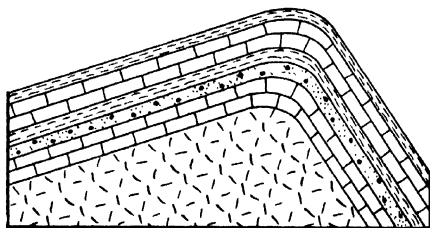
After the strike of any rock is determined, the position of the bed with respect to the horizontal is expressed as *dip*. The amount of dip is a vertical angle instead of a compass direction, but it is always measured in a direction at right angles to the strike and downward from the horizontal plane. Dips therefore vary from 0° in horizontal

Different types of anticlinal folds: (a) symmetrical, (b) asymmetrical, (c) overturned, (d) recumbent, (e) fan-fold, and (f) isoclinal.

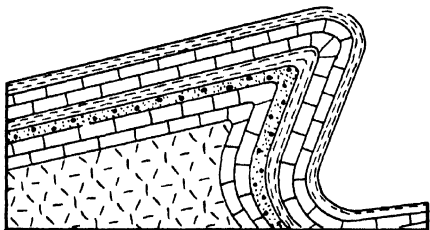
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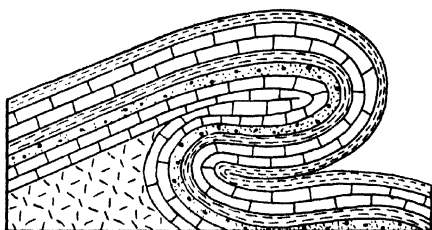
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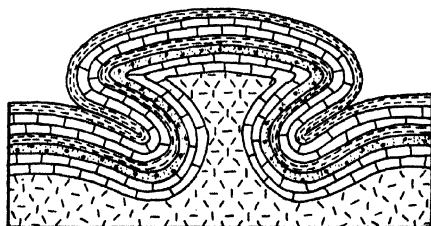
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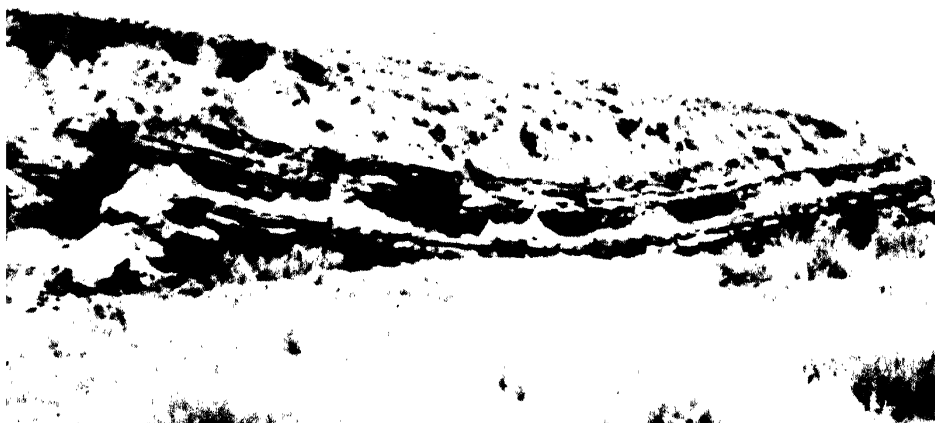


e



f





Oklahoma Geological Survey, photograph by S. L. Schoff

Syncline in Permian rocks.

Sharp folding in limestone.

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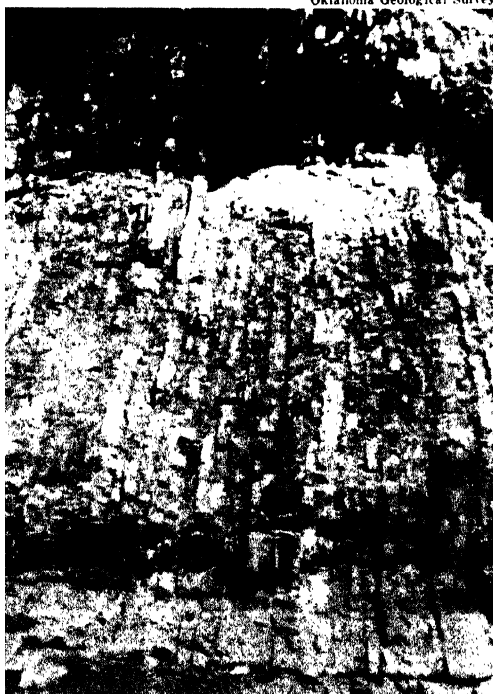
beds, to 90° in vertical beds. If the rocks have been completely overturned it is customary to indicate the dip in the usual manner but to add the word *overturned*.

Types of folds. When the layers of rock are tilted so that they dip in one general direction, both the terms *homocline* and *monocline* have been used to designate such a structure. In this book the term *monocline* will be restricted to those parts of homoclines which are locally steeper than the general dip of the structure (illustration, p. 249).

Sometimes the conditions are just opposite, and there is a local flattening of the dip. This is called a *structural terrace*. Again, the rocks may continue with approximately uniform rate of dip. This may be called a *plane homocline* (illustration, p. 249). If the dip of a homocline decreases, it is referred to as a *synhomocline*, while if the dip increases it forms an *antihomocline*. An upward longitudinal wrinkle is a *nose*, while a downward wrinkle of similar position would be a *chute*. (See the diagrams on page 249.) Actually, few of these terms are in common use. The terms *nose* and *structural terrace* are the ones used most frequently.

When rocks dip in two opposite directions, the resulting fold is called an *anticline* if the beds are arched up so that the dip is away from a central axis, and a *syncline* if the beds are downwarped so that

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These thin beds of limestone stand almost on edge, the result of intense crustal movements within the earth. As if further proof were necessary, we can find marine fossils in many limestone deposits, as in those shown at the left, which attest to the fact that the beds were once the flat bottom of some shallow sea. The steep angle at which these beds have been tilted gives ample evidence of the huge horizontal or compressive forces that create mountains.



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Overturned fold.

they dip toward a central axis (illustration, p. 251). These folds exist in many varieties. They may be symmetrical, asymmetrical, overturned, recumbent, isoclinal, or fan-shaped. These types of folds are shown in the diagrams on page 250. Structural arches of low dip but great size, perhaps covering an area equal to that of several states, are called *geanticlines*; down-folds of correspondingly huge dimensions are *geosynclines*.

In some instances folding causes rocks to dip in all possible directions. If the beds dip downward toward a central point or area, the resulting fold is termed a *structural basin*. If the layer dips outward away from a central point or area the word *dome* is applied to the fold. Domes are much more common than basins and arise from a variety of causes. Some appear to be due to the intrusion and crystallization of salt, and are referred to as salt domes. They are particularly numerous along the Gulf coast of Texas and Louisiana. Others are the result of igneous intrusions, such as those in the Henry Mountains of Utah. Domes which result from differential folding are likely to be irregular in shape rather than circular or elliptical.

Again it should be emphasized that it is extremely rare for the surface of the ground to correspond to the position of the rock folds below. Indeed, it is common to have reversed relationships, with topographic valleys over anticlines, such as Turner Valley, in Alberta, Canada, and flat land over the domes, as is the rule along the coast of Louisiana.

FAULTS

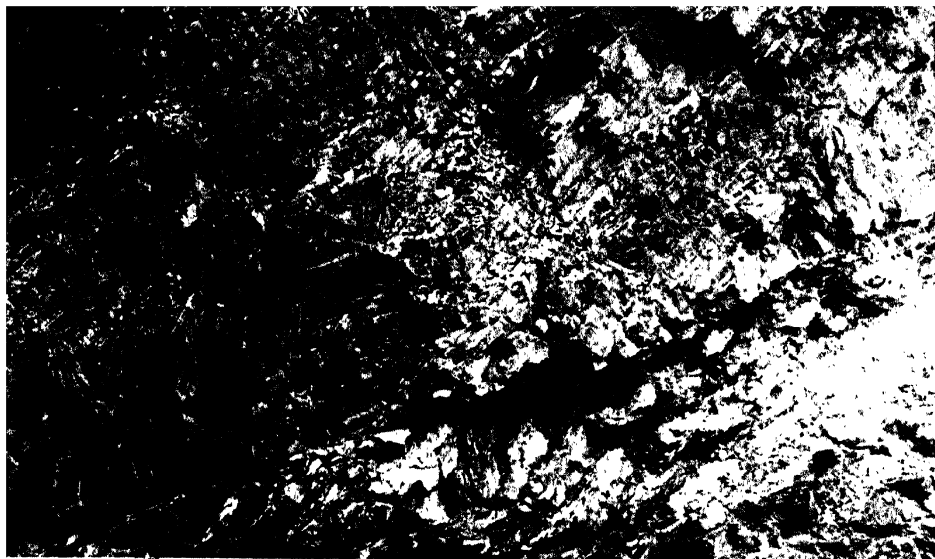
Causes and kinds of faults. A fault, as has been stated, is a break in the rocks accompanied by a relative displacement parallel to the plane of the break. The actual movement may be only a fraction of an inch, or the total displacement from a series of movements along the same general fracture line may amount to 50 or more miles. Faulting is the principal cause of earthquakes, which is another term for the tremors set up by the frictional resistance between the two opposing masses of rock moving along a fault plane.

The two principal types of stress to which all material is at times subjected are *tensional* and *compressional*. Often it is impossible to determine which of the two is the dominant stress, as they act together. The direction of maximum compression is at right angles to the direction of maximum tension. For example, as a rubber band is stretched, it decreases in thickness and width. Or if a thick sheet of lead or copper is compressed so as to reduce its thickness, the length and breadth of the sheet will increase. Solids break more easily by tension than by compression; therefore, it is to be expected that most of the faults found in the rocks of the earth would be due to tension. If the vertical cross section of a fault indicates that the rocks have been pulled apart, it is assumed the fault was due to tension and the fault is said to be *normal*. If the opposite conditions exist and the rocks have been pushed over each other, the fault is called *reverse*. (Illustration, p. 257.)

Small fault in shale on Batler Creek, Garfield County, Oklahoma.

Oklahoma Geological Survey





Standard Oil Co. (N.J.), photograph by Lofman

Overthrust fault in chert.

The lowest point in America. Bad Water, Death Valley, is 279.8 feet below sea level, lying on the floor of a graben.

National Park Service



Normal faults are found in all kinds of rocks and associated with all kinds of rock folds, but reverse faults are seldom observed except where the rocks have been rather closely folded. When associated with over-turned folds the reverse faults are often called *thrust* or *overthrust* faults.

Fault terminology. A series of normal faults parallel in direction but with overlapping ends are said to be *en echelon*. If a block of rock is lower than blocks on either side by virtue of parallel normal faults on either side, it is referred to as a *graben*. If higher, it is called a *horst*. (See diagrams on pages 259 and 260 and the photograph on page 255.)

A series of parallel normal faults which dip in the same direction are referred to as *step* faults. (See diagram of all types of faults mentioned above, p. 259.)

There are certain terms applied to faults regardless of whether they are normal or reverse. The more important of these are fault plane, heave, throw, hade, hanging wall, footwall, upthrow side, and down-throw side.

The *fault plane* is actually not a plane but is the surface or zone along which the fracture occurs. It is often characterized by a zone of broken rock fragments ranging from dust to large angular blocks. The term *fault breccia* is applied to rocks resulting from the cementation of such fragments.

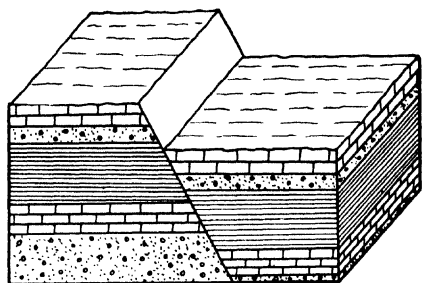
The *heave* of a fault is the apparent horizontal displacement when the fault is viewed in vertical cross section.

The *throw* is the apparent vertical displacement when the fault is viewed in vertical cross section. For normal faults the throw usually exceeds the heave but in reverse faults the heave is usually very much greater than the throw.

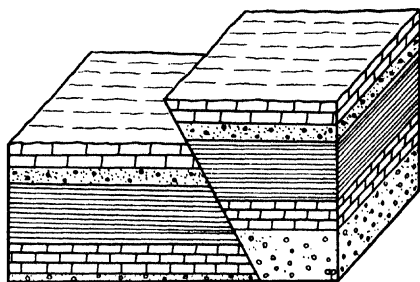
The *hade* is the angle between the fault plane and the vertical. It is therefore the complement of the dip of the fault plane.

Unless the fault plane is vertical there will be an upper and a lower side. The *hanging wall* is the side above the fault plane, while the side below is called the *footwall*.

Although one can never be positive which side of the fault has actually moved, it is easy to determine the side which has moved up or down with reference to the other side of the same fault. Conse-

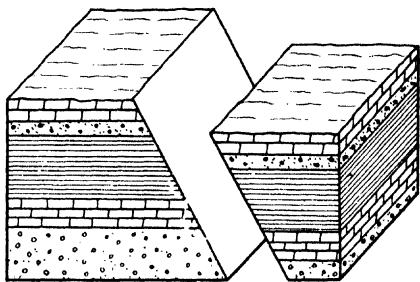


a



b

Block diagrams of faults: (a) normal fault, where the movement is down the dip of the fault plane; (b) reverse fault, where the movement is up the dip of the fault plane; and (c) normal fault, in which the movement is diagonal along the fault plane.



c

quently, we have the apparent *upthrow* side and the apparent *downthrow* side. (See diagram, p. 260.)

If a fault extends to the surface of the ground it may cause an abrupt change in level in the nature of a steep slope or even cliff, whose location corresponds approximately to the position of the upper part of the fault plane. Such a topographic feature is referred to as a *fault scarp*. Erosion may soon completely destroy such a feature unless some very resistant formation occurs on the upthrow side of the fault and thereby preserves the scarp. Whether or not a fault scarp is present, there is usually some evidence of the existence of a fault which extends to the surface. This may take the form of an abrupt change in soil or rock or even vegetation. In some instances the broken rock fragments along the fault surface may be visible. In other places a line of springs may indicate the location of the fault. This intersection of a fault plane with the surface is called the *trace* of the fault. In flat areas the trace will usually be a straight line, but in irregular topography the trace will usually curve according to the hills and valleys which it crosses. Note illustrations on pages 262 and 264.

Rocks along the zone of the fracture will be subjected to considerable friction as they slide past each other. This not only causes fragments

to be broken from each of the opposing walls but sometimes causes both fragments and rock walls to be scratched, grooved, and polished. A rock which has been smoothed in this manner is referred to as a *slickensides* (illustration, p. 261), and thereby becomes one of the best possible evidences that faulting has taken place.

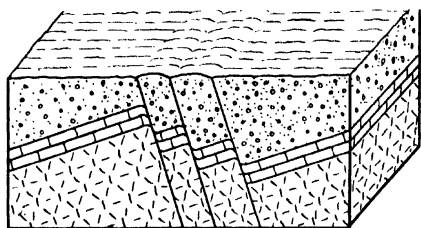
Both faulting and folding as well as jointing exert a profound influence upon the character of the topography when they are well developed. Many small stream valleys of central New York have their courses determined almost entirely by the jointing of the shales over which they run. In closely folded areas linear topography nearly always develops. The resistant beds outcropping on the sides of the folds make hogback ridges like those of the Appalachian Mountains. When faulting has occurred in comparatively recent time, geologically speaking, linear valleys and ridges result. This is beautifully illustrated by the topography of California west of the Great Valley.

EARTHQUAKES

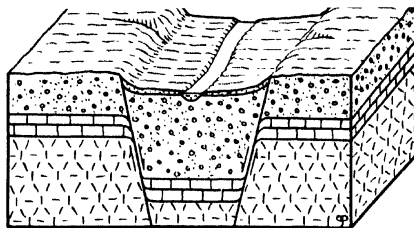
One of the most widely recognized results of faulting is the earthquake. A very small amount of displacement along a fault plane may cause an earthquake of unusually severe proportions. The sudden slipping of a jagged rock surface past another irregular rock surface will result in a series of sharp tremors which may travel hundreds or even thousands of miles through the denser rocks within the earth. These earthquake waves travel both vertically and horizontally. If there is an appreciable thickness of loosely consolidated material on the surface, this may be thrown into large waves which prove very destructive to buildings, bridges, highways, and dams.

To understand this effect one need only recall what happens when a hard blow is struck with a sledge on a wood floor covered with a layer of sawdust or dirt. The relatively solid boards of the floor move very slightly under the impact but the loose material on top is greatly disturbed.

Earthquakes are accompanied by a low rumbling noise, so low-pitched as to be inaudible to some people. In a severe earthquake this sound may become a deafening roar, and the ground may exhibit a violent twitching or wriggling motion, the surface sometimes being thrown into a series of wavelike undulations. Fissures frequently open

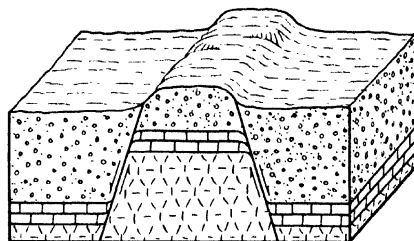


a



b

Cross-sectional diagrams showing (a) step faulting, (b) graben fault, and (c) horst fault.



c

in the ground; these may be irregular in arrangement or may present a parallel or radiating configuration. These fissures, which may vary in length from a few feet to several miles, may open and close repeatedly.

Changes in level accompany some earthquakes. An earthquake occurring in Iceland in 1875 resulted in a depression of the surface of 65 feet, while one affecting parts of Alaska in 1899 caused an elevation of 47 feet. Changes in the distribution of surface and subterranean waters are often brought about. Rivers change their courses, lakes are sucked underground or new ones appear, fountains and springs may appear suddenly or old ones dry up. An instance is reported from Iceland of the appearance of a fountain which spouted to an estimated height of 600 feet.

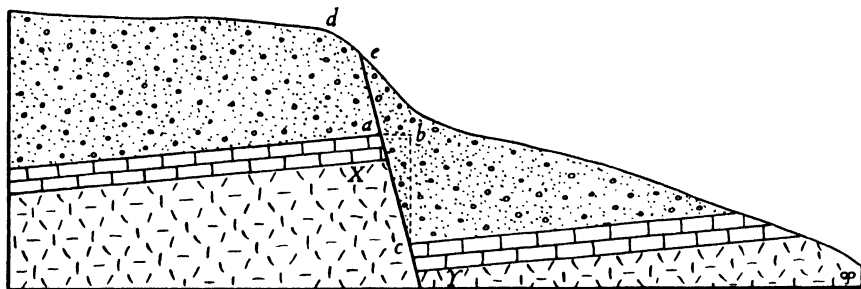
During an earthquake water may gush out of fissures or from isolated points, carrying quantities of loose sand or mud, frequently accompanied by small flakes of mica. The sand may completely blanket the region over a considerable area; it may fill fissures and harden into sandstone dikes; or it may form "craterlets"—funnel-shaped depressions lined with sand and leading at their inferior end to a narrow, sand-choked tube. Mud may be piled into cones known as mud "volcanoes," a number of which are shown in the photograph on page 263.

Earthquakes are often accompanied by a disagreeable, nauseous odor, the result of the release of hydrogen sulfide from decaying matter in the soil.

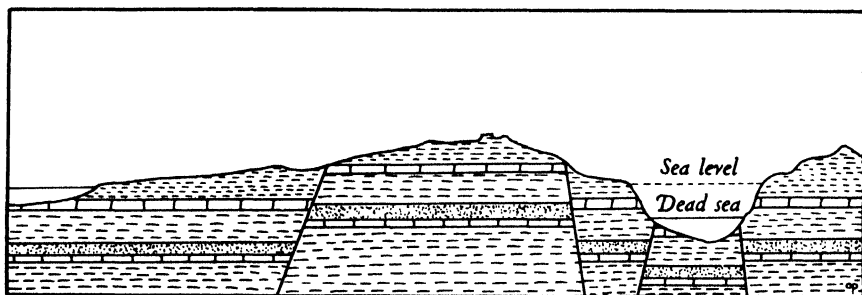
The sudden jar which constitutes an earthquake is detected by the instrument known as the seismograph, which consists essentially of two units, one of which is designed to make a continuous mark upon the other. One of the units vibrates with the earth, the other is kept stationary. Earthquakes are located by first determining their distance from the recording station. Since earthquake waves are of several kinds, traveling at different rates, the distance of the source of the disturbance can be measured by the time elapsing between the arrival of different kinds of waves.

To determine the exact location of an earthquake disturbance, the co-operation of several stations is necessary. Thus if it is found that an earthquake has occurred 1800 miles from Chicago, 1400 miles from Washington, and 2400 miles from Los Angeles, the center of the disturbance is definitely located—in this instance, in the Caribbean Sea.

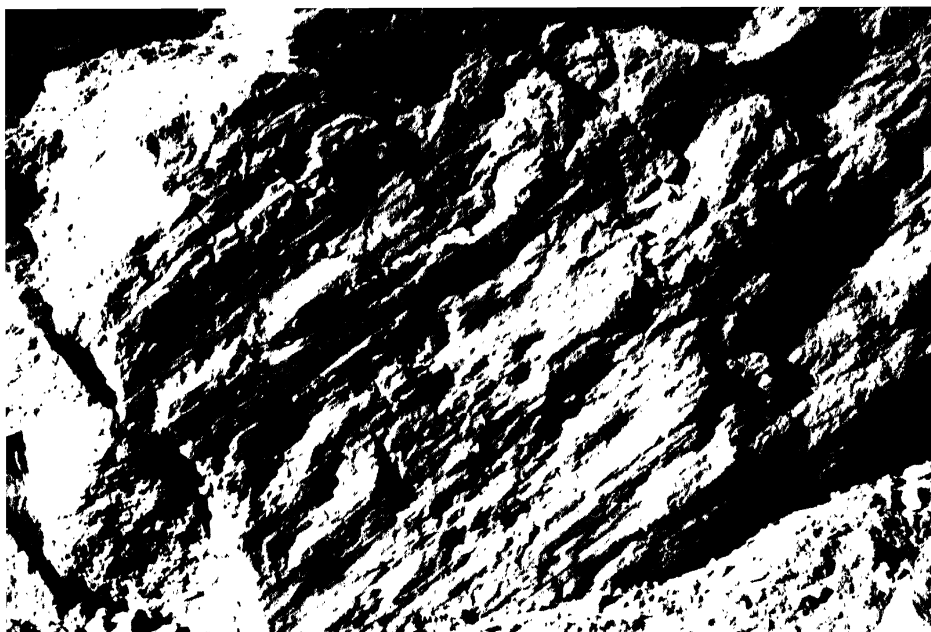
The place at which the faulting responsible for an earthquake takes



Cross-sectional diagram to illustrate the terminology of faults: ab is the heave; bc is the throw; de is the fault scarp; angle acb is the hade; x is the upthrow side, and for this fault is also the footwall; y is the downthrow side, and for this fault is also the hanging wall.



The Dead Sea occupies a rift valley, or graben, in an intensely faulted region.



*Slickensides.*¹

place is known by the term *focus*. This region almost always lies within a few miles of the surface of the earth, in the zone in which rocks tend to fracture, rather than flow. There have been a few cases, however, in which earthquakes appear to have originated at depths of several hundred miles; satisfactory explanations of such occurrences are still wanting.

It should be kept in mind that the earthquake is a tremor or series of tremors and is a result rather than a cause. Earthquakes may, of course, be caused by explosions, landslides, collapse of cavern roofs, or volcanic activity, but in nearly all instances some form of faulting is responsible. The fact that most earthquakes that have occurred in historical time were located in one of two great belts of the earth merely indicates that those areas are still undergoing adjustments because of unbalanced differences in elevation, density of rocks, or sedimentation. No satisfactory method has ever been devised to predict when earthquakes will occur, but instruments are in use which record tremors that originate thousands of miles from the recording instrument.

¹Reprinted from *Engineering and Science Monthly*, California Institute of Technology. Photograph by J. P. Buwalda.



Shell Oil Co., Spence Air Photos

Trace of the San Andreas fault, fruitful source of earthquakes along the Pacific coast.

By means of these records it has become evident that most earthquakes of modern times have taken place either around the margin of the Pacific Ocean or in a second belt at nearly right angles to the first one, passing through the Mediterranean area, Central America, and the East Indies. The diagram on page 265 gives an idea of how intensely faulting has affected one active earthquake area.

From the geological standpoint earthquakes are of very minor importance, as most of the phenomena attributed to earthquakes are really due to faulting rather than to the tremors. Nevertheless, they are of great economic importance because of the wholesale destruction of life and property which often accompany or follow them. Much of this, however, is due only indirectly to the tremors themselves but rather to the enormous sea waves sometimes created or to the fires which follow the disruption of water mains and fuel and power lines in cities affected. Occasionally, great destruction has resulted from earthquake-induced landslides.

There is probably no area of appreciable size on any continent that has not suffered earthquakes at one or more times during the geologic past. Faulting, the principal cause of earthquakes, has been observed in all parts of the world. It is only in those areas where the earth is still undergoing readjustments that earthquakes are now likely to occur. If the stresses accumulate over a long period of time before they are relieved by fracturing of the earth, the resulting earthquake is usually severe. If the area affected happens to be in a densely populated region, the effect on life and property may be so disastrous that the earthquake is considered a national calamity. A much more severe quake in a sparsely settled region would be known only by the records made on far distant seismographs. Fortunately many of the countries where earthquakes are almost a monthly or even weekly affair seldom have severe earth shocks, because the readjustment stresses are relieved before they build up to cause a major earth fracture. This is especially true in Japan, California, and Central America. Proper construction of buildings in such areas has made it possible to reduce the property loss to a minimum during periods of earthquake tremors.

UNCONFORMITIES

When a series of sedimentary beds is deposited without any appreciable interruption they are said to be *conformable* upon each other. All the agencies of deposition are subject to fluctuation in ability to transport and deposit sediments; therefore, it is to be expected that

Geological Survey of Canada

These curious mud "volcanoes," in Burma, were formed when mud was squeezed out of the ground along fault planes. In the same way, faults often permit the flow of underground water, petroleum, and natural gas. Oil-bearing or water-bearing strata, on the other hand, are sometimes cut off and brought into juxtaposition with impervious rock which seals off the porous rock and prevents any further underground movement of the water, oil, or gas.



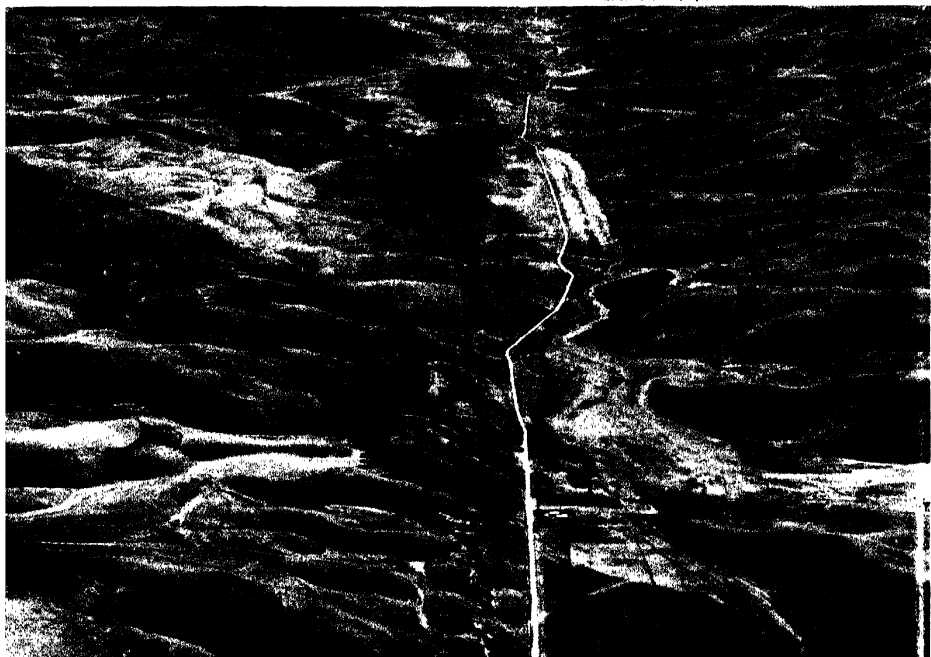
there will be changes from coarse to fine and back to coarse material as the supply of material and the carrying power of the agent change. This does not prevent a conformable succession of beds being laid down.

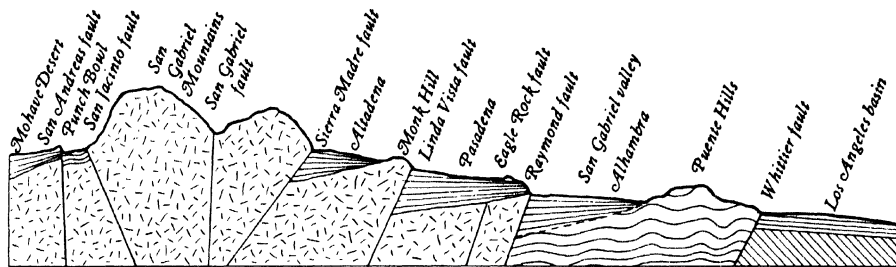
Deposition may be completely halted by uplift and the newly deposited material may thereby become subject to erosion and transportation to a new site. These uplifts may be in the nature of a gentle upwarping of a large area, or the intense folding and faulting of either small or large regions. These interruptions of deposition may be of short duration, or thousands or even millions of years may elapse before the area once more receives deposits of sediments. Whether the interval is short or long, there will exist a gap, or hiatus, in the sedimentary record at that place. Such a break is referred to as an *unconformity*.

In general, unconformities are of two types. The first type, called an *erosional unconformity*, or sometimes a *disconformity*, is characterized by a succession of parallel layers of rock with some beds, or even formations, completely omitted. (Illustration, p. 269.) The unconformity is that surface which separates the lower, older beds from the upper beds and occurs at the place where the missing middle beds should normally occur. This may be indicated by an erosional surface

A dissected fault scarp. California.

Shell Oil Co., Spence Air Photos





Cross section from the San Gabriel Mountains to the Los Angeles Basin, showing the intensely faulted character of this region. Sediments have accumulated in basins formed by the tilting of fault blocks.¹

characterized by a zone of weathered rock and an uneven or irregular contact between the upper and the lower beds. On the other hand, this kind of evidence may be wholly lacking, and the only indication may be the absence of certain beds which have elsewhere been observed to occur at this horizon. Sometimes a gap in the fossil record or an abnormal sequence of sedimentary deposits may be the only evidence of such an unconformity. Many unconformities of this type have been discovered by the samples of rock encountered in the drilling of deep wells. Whenever any well one thousand or more feet in depth encounters a zone of weathered rock it is almost certain that an unconformity has been encountered.

The second type of unconformity is called a *nonconformity*, or an *angular unconformity*. This differs from the preceding variety in that the sedimentary layers below the unconformity are not parallel to those above. Folding, uplift, and erosion of the lower, older layers occurred before the upper, younger beds were deposited. Here too there will usually be an erosional surface and weathered zone, but the lack of parallelism of the layers above and below indicates a period of tilting or folding *before* the younger rocks were laid down. An excellent example is shown on page 269.

In some instances this folding was accompanied by igneous intrusions or by metamorphism, but the younger rocks were not so affected.

These nonconformities are extremely important when we try to determine the probable position and character of sedimentary formations far below the present surface of the ground. In those states where hundreds or even thousands of deep wells have been drilled, it has

¹Courtesy of *Engineering and Science Monthly*, California Institute of Technology. Redrawn from the original.

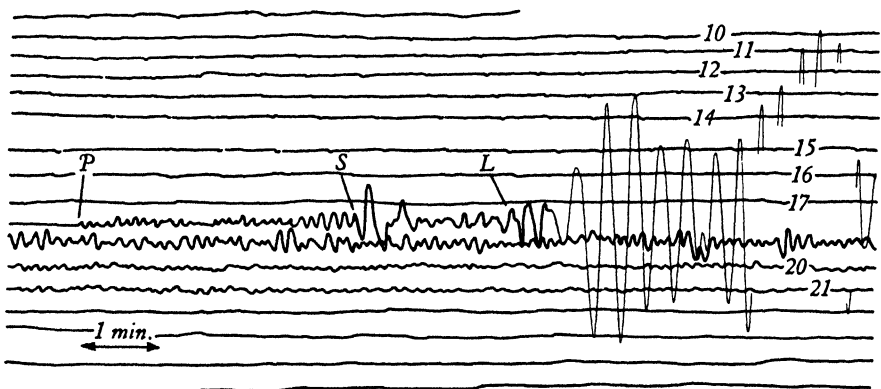
frequently been found that the older and deeper rocks have once been folded and uplifted into mountain ranges which were later eroded or even peneplained before being covered up by the younger sediments. These "buried hill" structures have been found in Kansas, Oklahoma, and Texas, and doubtless exist in many other states. There is little, if any, indication at the surface of their presence in the underlying rocks.

THE THEORY OF ISOSTASY

Time and again geologists have found marine deposits of great thickness which must have been laid down in shallow water, since even their lowest sections contain fossils of shallow-water plants and animals. In southern Louisiana, for example, there exists a delta deposit of such sediments believed to be about 30,000 feet thick, more than twice the depth of the Gulf of Mexico. In many cases, also, thick delta deposits show by the variation in the coarseness of their sediments that the regions from which these sediments were derived were undergoing erosion occasionally accelerated by regional uplift.

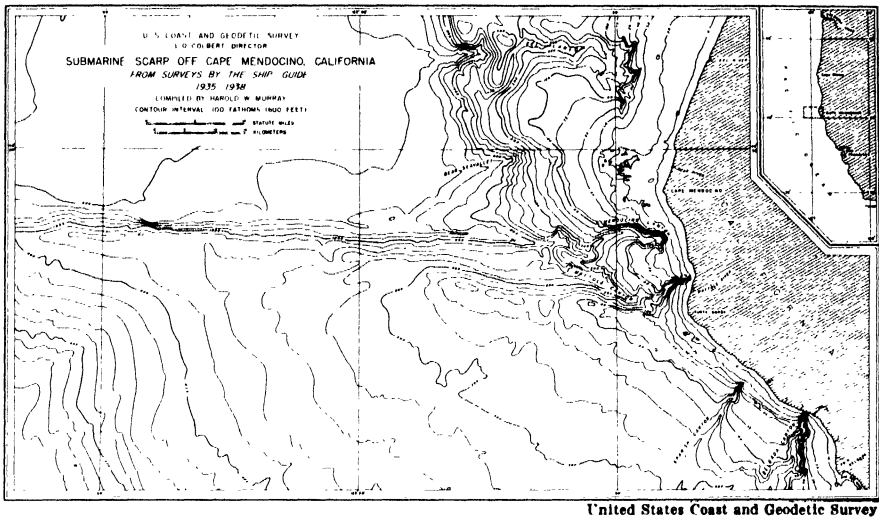
Apparently, the deposition of large amounts of sediments in any place causes, or is at least correlated with, subsidence of the region in question; similarly, the removal of substantial quantities of rock material is associated with an elevation of the region. Why?

To answer this question, the theory of *isostasy* has been advanced.



A seismogram, or record made by a seismograph, of an earthquake.¹

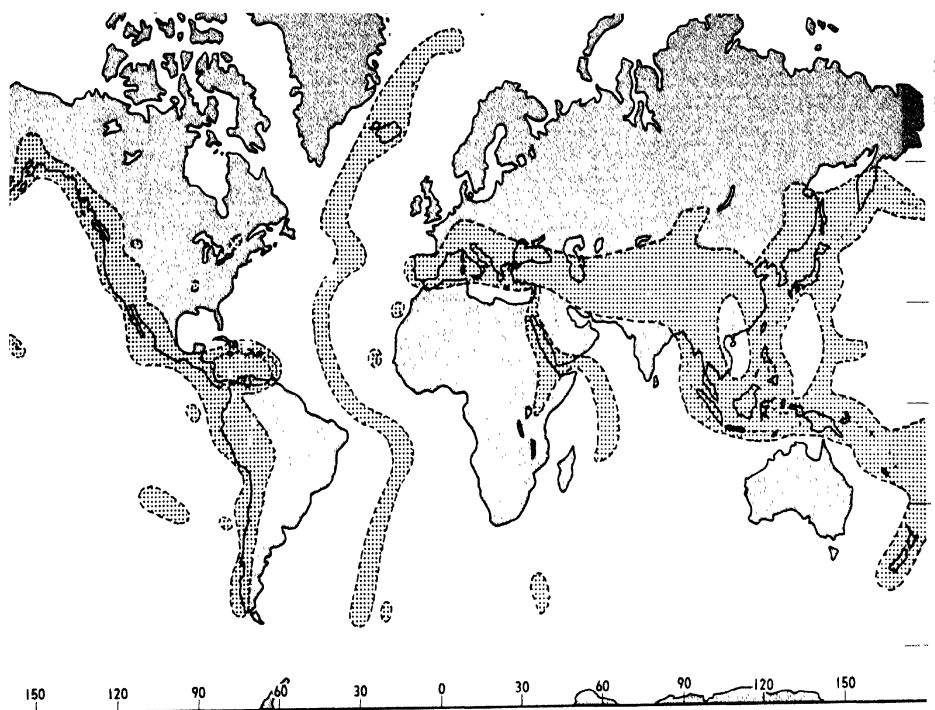
¹Courtesy of *Engineering and Science Monthly*, California Institute of Technology. Redrawn from the original.



Many earthquakes are the result of faulting on the sea bottom, such as may have produced the submarine cliff shown here. This cliff is from one-half to one mile high, and extends more than 60 miles from the shore. Note also the remarkable series of submarine canyons, one of which is practically in contact with the shore.

This theory postulates that the crust of the earth is kept in essential balance; that an overloaded section of the crust slowly sinks, while one which is being extensively eroded rises, until gravitational equilibrium has been established. According to this theory, any area of the earth's surface (of considerable extent) covers a segment which, extended to the earth's center, has the same weight as any other segment of equal surface area. The length of these segments does not matter; one of them may be chosen from the top of the Plateau of Tibet or the Antarctic Continent, another from a sea-level plain, and yet another from the floor of the sea.

If this be true, it follows that the higher lands of the earth must consist of and be underlain by rock that is lighter than average, and that sections of lower altitude, such as the sea beds, are formed of rocks of greater-than-average density. This conclusion is supported by direct evidence. Not only do we have the testimony of earthquake waves that the continents consist mainly of granitic rocks, while the ocean basins are underlain by basaltic materials, but certain experiments confirm the thesis that highlands are built of lighter stuff than lowlands



The earthquake belts of the world.

and sea floors. A plumb bob suspended over the ocean or the flat steppes of Russia hangs vertically, drawn straight downward by the pull of gravity. Near a large mountain the bob is slightly deflected by the pull of the mountainous earth mass; but the deflection is not so great as it should be, theoretically, if the mountain consisted of materials of the average density of the rocks of the crust. Again, a pendulum swings more slowly over a mountain than it should upon the assumption that the rocks of the mountain are of average density.

It may be that as a mountain system is worn down and its detritus deposited in epicontinental waters, settling of the region receiving the sediments causes subcrustal movements of plastic rock material from beneath the site of deposition toward the region in which erosion is occurring. The intrusion of this deep-seated material may result in the uplift of the mountainous district. On the other hand, the phenomena of uplift and depression may involve no lateral movement of material deep beneath the surface, but only vertical compression and expansion of rock as deposition and erosion alter gravitational stresses.



Oklahoma Geological Survey, photograph by C. L. Cooper

Erosional unconformity in limestone. Kiowa County, Oklahoma.

An angular unconformity. Basal conglomerate (Wasatch) lying upon the Laramie sandstone.

United States Geological Survey, photograph by Fisher



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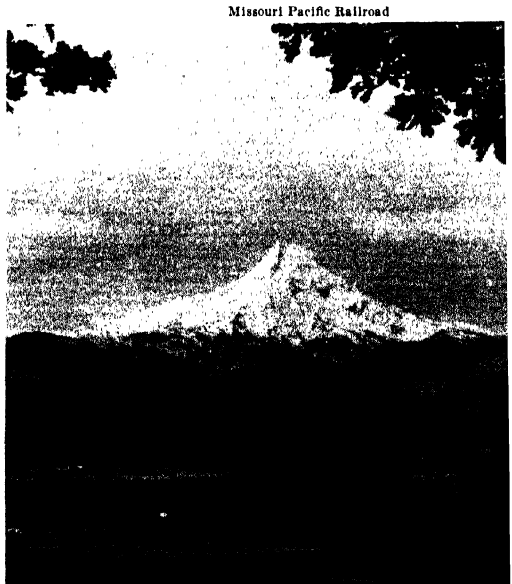
XII · MOUNTAINS



A mountain is a region of limited surface area that is notably elevated above its surroundings. In areas of slight relief any conspicuous hill may be called a mountain. Stone Mountain, near Atlanta, illustrated on page 273, is very prominent because it rises abruptly from a nearly level plain. In the plains sections of Texas and Oklahoma, elevations of but a few hundred feet are called mountains. In more rugged regions, the term is generally applied to the higher peaks and ridges only, lesser eminences being designated as hills, ridges, or foothills.

By the elevation of a mountain is meant the height of its summit above sea level, although a statement in these terms conveys only a general idea of the local prominence of the feature. A topographic knob with an elevation of two hundred feet would be quite conspicuous from a distance of many miles if located in a state like Florida, where the general elevation above the sea is rarely more than a few feet. On the other hand, the highest mountain peaks of Colorado and Wyoming rise from a base which is itself more than a mile above sea level; the actual height of these mountains, therefore, is equivalent only to their altitude above this base.

Mount Hood, Oregon, one of the many large volcanoes of the Cascade Range. Rising 11,245 feet above the sea, this great mountain was a landmark for early explorers and is today much sought out by skiers and mountain climbers. Although perpetually covered with snow, it still emits sulphurous fumes. Definite volcanic activity was reported, but never confirmed, about the middle of the past century.



The steepness of mountain slopes is nearly always overestimated by the casual observer and not infrequently by the trained geologist. Vertical and even overhanging cliffs occur, but the longer slopes seldom exceed 35°, and in most cases are very much lower. It is equally true that horizontal distances in mountainous regions are nearly always underestimated. A peak which is judged to be no more than a mile or two distant may well prove to be two or three times that far away. Human judgment is also often in error in attempts to estimate the highest points of distant mountain tops.

CLASSIFICATION OF MOUNTAINS

An entirely logical classification of mountains based upon their mode of origin is hardly possible to prepare, for no mountain exists which has not been formed, or at least modified, by more than a single process. However, for the sake of convenience in study, the following classification may be used:

- Mountains of accumulation
 - Volcanic cones
 - Wind deposits
 - Glacial deposits
- Mountains of erosion
- Mountains produced by diastrophism
 - Elliptical uplifts
 - Zone uplifts (geosynclinal mountains)
 - Fault blocks

A large group of mountains of essentially the same character, uplifted at approximately the same time by the same earth movement, is said to constitute a *mountain system*. Thus we speak of the Andes system. A portion of a system consisting of neighboring parallel ridges or of one complex ridge is termed a *range*. The Big Horn range, the Front range, and the Sangre de Cristo mountains are well-known ranges of the Rocky Mountain system. The term *mountain chain* is employed somewhat loosely, generally to signify a long mountainous belt which may contain systems of various origins and types. A number of geographically associated systems or lesser units forming a very extensive belt constitute what is known as a *cordillera*. Thus the Rockies and all the mountains west of them in North America form a cordillera.

ORIGIN OF MOUNTAINS

Mountains of accumulation. To this class of mountains belong all the types of volcanic cones described in the chapter on volcanoes. Included are some of the best-known mountains in the world, such as Mt. Fujiyama in Japan and Mt. Vesuvius in Italy, as well as most of the smaller mountainous islands of the Pacific Ocean area. Volcanic activity produces not only isolated peaks and cones but often affects zones of considerable size, producing groups of volcanic mountains, or operates along lines, resulting in the formation of chains or ranges. An example of the latter type of occurrence is seen in the Aleutian Islands of Alaska, which have been built up from the sea bottom by volcanic activity, forming a range about 1000 miles long.

Masses of volcanic debris of mountainous size may accumulate quite rapidly. Parícutin (p. 316), the new volcanic mountain in southwestern Mexico, erupted suddenly in a relatively flat cultivated field, and in two or three years had built a cone with an elevation of more than a thousand feet above its base. Similar cases have been known, and there have doubtless been many instances of such rapidly growing mountains during geologic time.

The amount of material which has been transferred to the surface from deep within the earth to form some of the larger volcanic mountains is almost incredible. In bulk the largest mountains of this kind exceed those of any other type. They may be built up from a deep

A monadnock, or residual mountain. Stone Mountain, Georgia.

United States Geological Survey, photograph by Hillers





Pan American Union

Highest point in the Western Hemisphere is the peak of Aconcagua, on the boundary line between Chile and Argentina. Elevation, 23,000 feet.

ocean floor until they reach elevations of two or three miles above sea level, and yet the slopes of their sides may be very low.

Occasionally sand dunes or glacial deposits, particularly kames and moraines, reach such size that they may be referred to locally as mountains. They are seldom known as such outside the immediate region in which they occur.

Mountains of erosion. Some mountains have resulted from the combined action of uplift and erosion, or from the erosion of plateaus caused by lava flows. We may see the effects of the early stages of dissection of an elevated mass in the Colorado Plateau in northern Arizona and the adjoining states. Here high elevation has given great impetus to the down-cutting of the streams, all of which tend to become gorges. Rising from the bed of the Colorado River are residual masses of mountainous height, and it is only a question of time until the entire plateau will be reduced to mountains and lesser eminences



Canadian Pacific Railway

Despite its Matterhornlike shape, Mount Assiniboine, Alberta, is a residual mountain, carved from horizontal rocks largely through the action of ice.

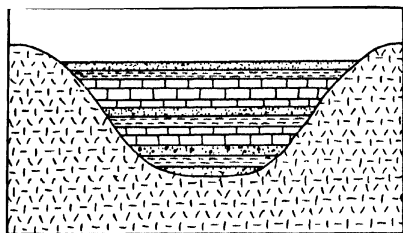
with intervening valleys. Later stages in the development of this type of mountain are to be found in the western part of the Ozark Mountains of Arkansas and in the Catskills of New York. In these mountains the rock layers are essentially horizontal and mountain summits are concordant in elevation. This smooth sky-line effect may also be present in a dissected peneplain developed on folded rocks, but is seldom seen in mountains of other types.

Mountains resulting from diastrophism. When a portion of the earth is buckled up by diastrophic forces, the result may take the form of (1) a broad upwarping of an area into a plateau which may cover hundreds or even thousands of square miles; (2) the more localized bulging of an elliptical area of perhaps twenty-five to one hundred miles in linear extent; (3) the crumpling and subsequent uplift of a broad and long zone where a great thickness of sediments had accumulated; or (4) the tilting of large blocks of the earth along great fault planes.

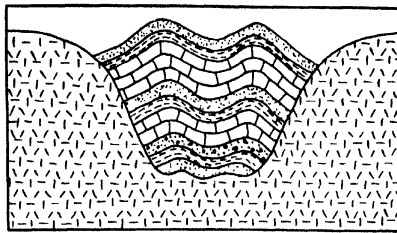
Each of these types of uplift, when followed by prolonged erosion, causes the development of its own peculiar type of mountain, each of which exhibits distinguishing characteristics that may be readily identified. The dissected plateau has been discussed in connection with mountains of erosion. The other types will be discussed individually in the following pages.

Between the Appalachian and the Rocky Mountains there are a number of comparatively small uplifts which because of their dissected condition have already been referred to as "geological windows." The Llano uplift of Texas, the Wichita and the Arbuckle Mountains of Oklahoma, and the Black Hills of South Dakota are of this kind. Each is an example of an elliptical uplift of relatively small extent in which a thick section of formations has been buckled up and eroded in such a manner that the older rocks once deeply buried are now exposed near the center of the uplift. These "windows" permit the geologist to study the edges of formations that elsewhere may lie miles below the surface.

The Black Hills are the result of a fairly simple domal uplift, but the other examples mentioned exhibit rocks that have been closely folded and faulted. The resistant formations along the sides of the eroded anticlinal folds result in peaks and ridges which follow the

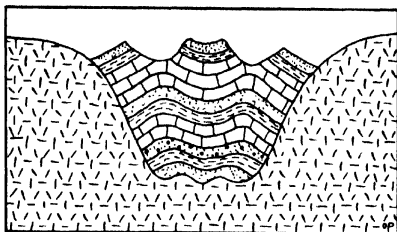


a



b

Highly idealized vertical cross section, showing the stages in the formation of geosynclinal mountains: (a) a broad geosynclinal trough after a great thickness of sediments has been deposited therein; (b) the same trough after lateral compression has narrowed the trough and folded the sediments; and (c) the same trough after erosion has carved mountains and valleys out of the sediments.



c

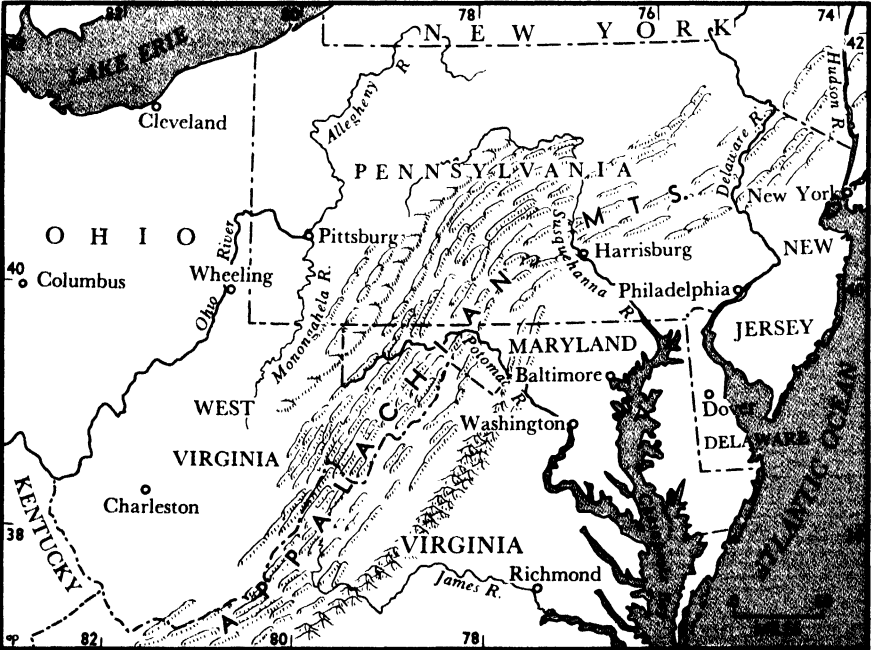
strike of the rocks. The valleys are developed in the weaker shale formations and are flanked by typical hogback ridges (illustration, p. 92). The actual shape of the individual peaks, ridges, and valleys is determined primarily by variations in the resistance of the rock material to the forces of erosion. When igneous rocks are present, they are generally more resistant than either sandstones or limestones, and therefore form the higher peaks. In the Black Hills the highest mountain, Harney Peak, consists of granite, although many of the lower mountains of the same area are of limestone. This same condition exists also throughout most of the Rocky Mountain region, despite the fact that thousands of feet of less resistant formations once covered the igneous rocks.

The great mountain systems of the world all belong to the group which results from diastrophism of the zonal type. The Alps, the Himalayas, the Sierra Nevadas, the Appalachians, the Rockies, the Andes, and hundreds of lesser units have been of this origin. Many of the greatest peaks and ridges of these mountains consist of granites or of some other type of crystalline igneous rock, and for that reason are frequently thought of as products of volcanic activity. The igneous mass that makes up the core of such mountains, however, is older than the sedimentary formations which occur on its flanks, and therefore

was not the cause of the uplift, but was itself lifted up along with the sediments which once lay on top of it.

A study of one of the great mountain systems shows that it consists of eroded sedimentary strata of great thickness overlying an igneous core. The thickness of these sedimentary rocks is of special significance. Formations which in the Mississippi Valley measure 4000 feet attain in the Appalachians a thickness nearly ten times as great. Still greater thicknesses of sedimentary rocks are exposed in the Rockies and in other mountain systems. So general is this condition that we may accept it as a general principle that great folded mountains form only where sediments have accumulated to an extraordinary thickness.

What of the sea in which these sediments accumulated? In many cases it measured hundreds of miles in length and many miles in width. It was not, however, as deep as the thickness of the sediments which accumulated in it might suggest; they are all of typical shallow-water materials, containing fossils of shallow-water organisms, and in



It is not hard to visualize the formation of these Appalachian ridges and the corresponding shortening of the crust in this section as results of lateral compression.

places exhibiting mud cracks, raindrop impressions, or other indications of shore conditions. A modern example is provided by the northern part of the Gulf of Mexico, in which sediments are now accumulating.

To explain the thickness of the sediments deposited in this shallow water, we must assume that the basin in which the water rested was slowly subsiding. The cause of this subsidence is not certainly known. It has been attributed to isostatic adjustment resulting from the weight of the accumulating sediments, but this interpretation is open to question. Perhaps the deepening geosynclines may rather be regarded as dents formed in the crust as a result of its efforts to fit tightly upon the shrinking interior of the globe.

The large quantity of material dropped in the sinking basin also calls for more than a casual explanation. The volume of these sediments is generally so enormous that it can be explained only upon the assumption that the lands from which they were derived were undergoing uplift, even as the adjoining geosyncline sank. This uplift, presumably, was intermittent in character, and did not always correspond in rate with the subsidence of the geosyncline; for we find evidences in the variability of the deposited sediments that conditions changed frequently. Sandstones bearing ripple marks alternate with shales and limestones, while disconformities and coal deposits point to times when the contents of the basins stood above the level of the water.

This picture of rising uplands adjacent to a sinking trough accords either with the theory of isostatic equilibrium between regions of erosion and of deposition (see page 267), or with the conception of slight crustal warping under the influence of lateral pressures.

The source of the sediments deposited in a geosynclinal basin is usually not hard to trace. The principal source is to be found in the highlands adjoining the basin, occurring in most cases on one side only. The position of this elevated region is indicated by a lateral gradation in the size of the deposited particles, which decrease in coarseness with distance away from their source. The thickness of the deposits also declines in the same direction. Upon the complete destruction of these highlands there will be left an area consisting of their basal rocks, which will be of much greater age than that of the rocks formed in the geosyncline. This region of ancient rocks along

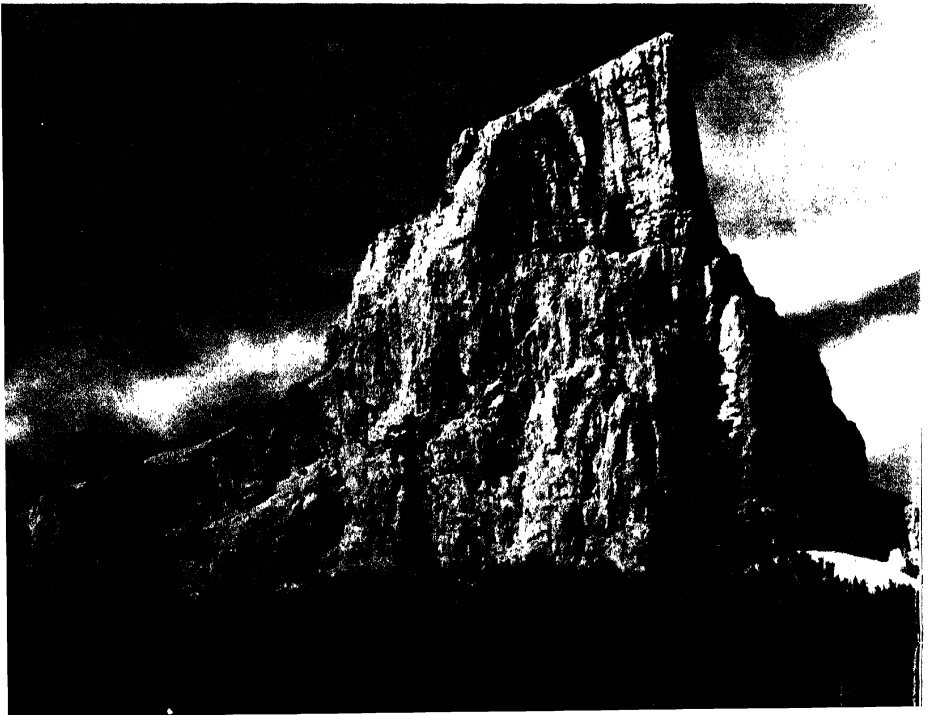
one side of folded mountains is still another indication of the location of the uplands from which their sediments were derived.

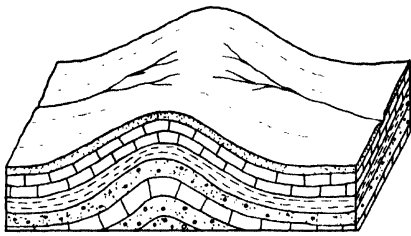
The accumulation of so thick a section of sediments produces a region of weakness in the crust of the earth. Sooner or later the weak rocks formed in the geosyncline begin to yield to the lateral pressures to which they are subjected, and are squeezed together into folds (see diagram, p. 277). The strata of many mountains exhibit strong angular unconformities; this means that folding commenced even before sedimentation in the basins had been completed. Ultimately the sediments are pressed together into a series of narrow folds. Sometimes such folds are comparatively simple, as in the Jura Mountains; more often many of them are so tightly compressed that their sides may be practically parallel, with many modifications of form which may make their history difficult to read. In the Alps, for example, compression has been so intense that many folds have been overturned, and some have flared out above, forming fan folds.

It has been pointed out that rocks are plastic only when under

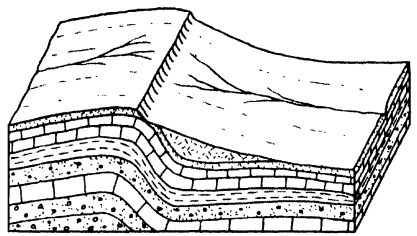
Moved many miles and left standing upon rock of a much younger age, this mountain is the product of one of the world's greatest fault movements. Chief Mountain, Montana.

Great Northern Railway



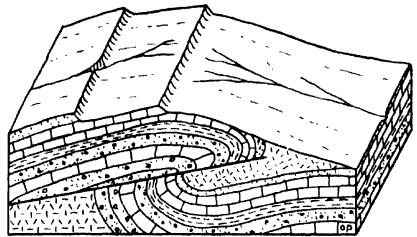


a



b

An overturned fold, passing into a thrust fault. (a) a normal anticlinal fold; (b) the fold becomes overturned; (c) fracture occurs, and one side is pushed over the other. In this way Chief Mountain in Glacier National Park, Montana (page 280), was transported many miles.



c

heavy load. Rocks subjected to mountain-forming movements, therefore, tend to fold at considerable depths—several thousand feet to several miles—and to fracture nearer the surface. Thus faults are common in nearly all folded mountains.

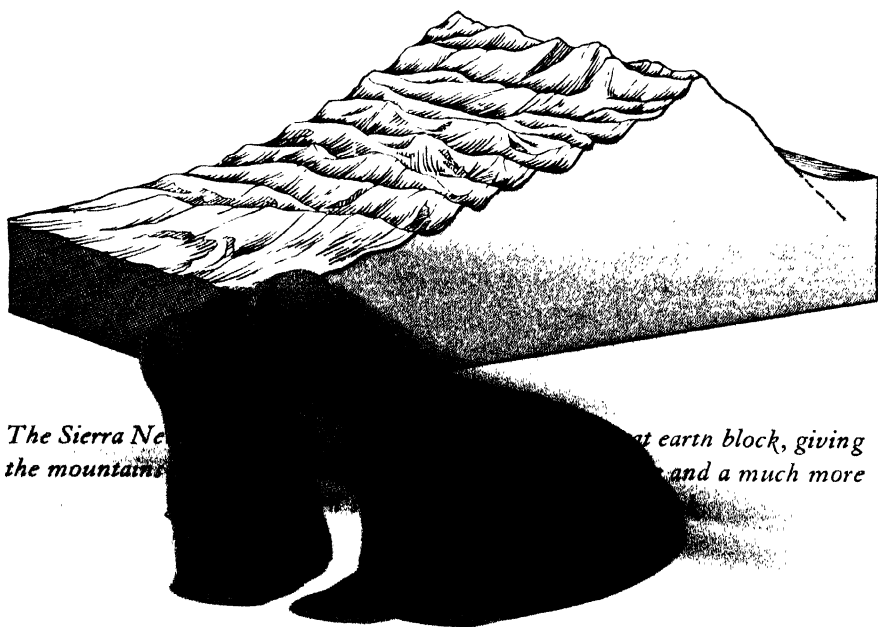
This crumpling and faulting of stratified formations is incidental to the shortening of the earth's crust. It has been estimated that in the Alps a shortening of more than 100 miles has been effected by pressures acting laterally upon the strata. The wrinkling of the Rockies reduced the width of the strata in this region by nearly fifty miles, while the Appalachian deformation resulted in even greater shortening, reducing the area covered by the Appalachian geosyncline to less than half its original size (see page 277 and map, page 278).

The extent to which the height of folded mountains may be attributed to compressional forces is a matter of dispute. Some geologists believe that the same forces which effect folding are also responsible for uplift; others hold that little actual elevation can result from lateral pressures, and some even contend that the folding of strata on a mountain-making scale causes at first a *sinking* movement, long before elevation begins. The possibility has been suggested that the rise of mountains is connected with the heating and consequent expansion of these rocks when they have been depressed deeply into the earth. It is probably safe to infer that most of the height of mountains of

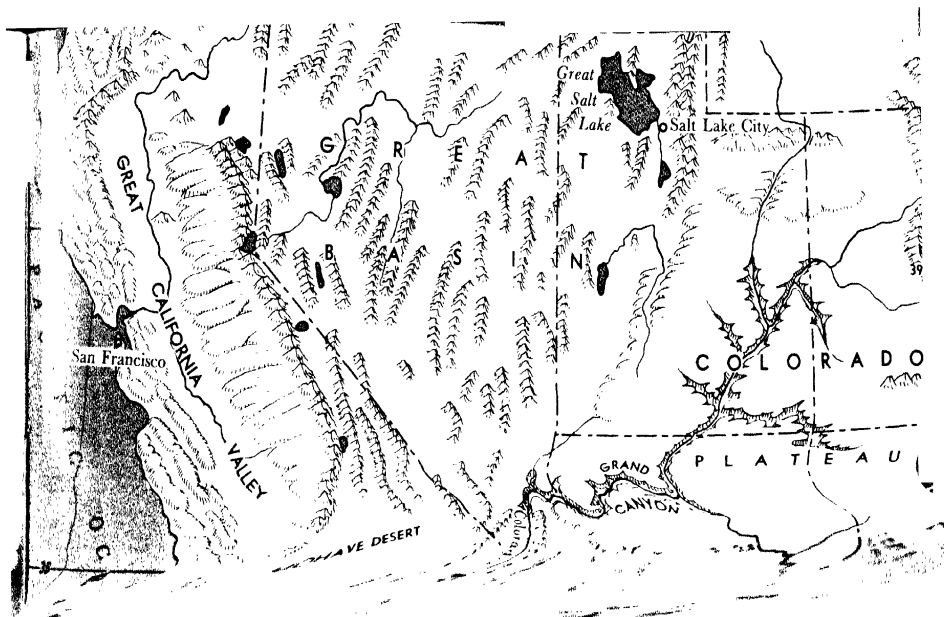
this type is not attained at the time of major folding, but that it is due to isostatic movements which follow at a much later date. Many mountains show clear evidence of having experienced repeated uplifts at long intervals following their formation.

Erosion, of course, begins as soon as elevation has brought the rising mountains above the sea. For a time uplift more than keeps pace with the forces of disintegration, but at length wind, water, and ice gain the upper hand. The shape of the mountains, at first determined chiefly by the structure of their rocks, feels more and more the influence of abrading streams and chiseling ice. Weaker rocks are washed away, leaving the more resistant jutting sharply into the sky as peaks and crags. These prominences too are in time worn away, and the mountains are reduced to rounded summits with gently sloping sides. Eventually the region may be peneplained. Uplift usually ensues, followed by renewed erosion, which again attacks principally the less resistant rocks, thus converting the more resistant ones into mountains, which usually take the form of long ridges. In these too will be worn away.

The earth today presents examples of *block uplift* and erosion. In the *Cascades* a block uplift and erosion. In the *Cascades* a block uplift and erosion. In the *Cascades* a block uplift and erosion. On the but a few miles *at Mt. Whitney, the highest peak in the United States* *leads down a precipitous east slope of more than 1000 feet to the mile*, toward the west, however, the surface of the block descends



The Sierra Nevada is a great earth block, giving the mountains and a much more



covered by sediments washed into the central valley of California.

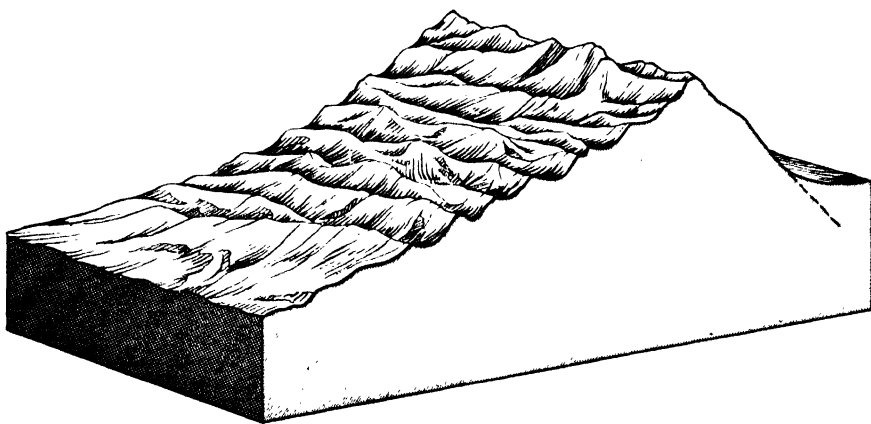
The Basin Range mountains of Nevada and parts of California and Utah consist of a large number of ranges with a general north-south trend; these have originated in faulting movements. The illustration on page 283 shows the location, general shape, and structure of both the Sierra Nevadas and the Basin Range mountains. The topography of this section is in pronounced contrast to that of the relatively undisturbed Colorado Plateau region.

Fault mountains are characterized by remarkably straight-lined boundaries. Rift valleys frequently adjoin the mountains, running parallel to the ranges. As with other mountains, erosion ultimately determines the shape to a great extent. More resistant formations are brought into relief, the upper slopes of the blocks are worn back, and the lower slopes covered by weathered and eroded debris from above.

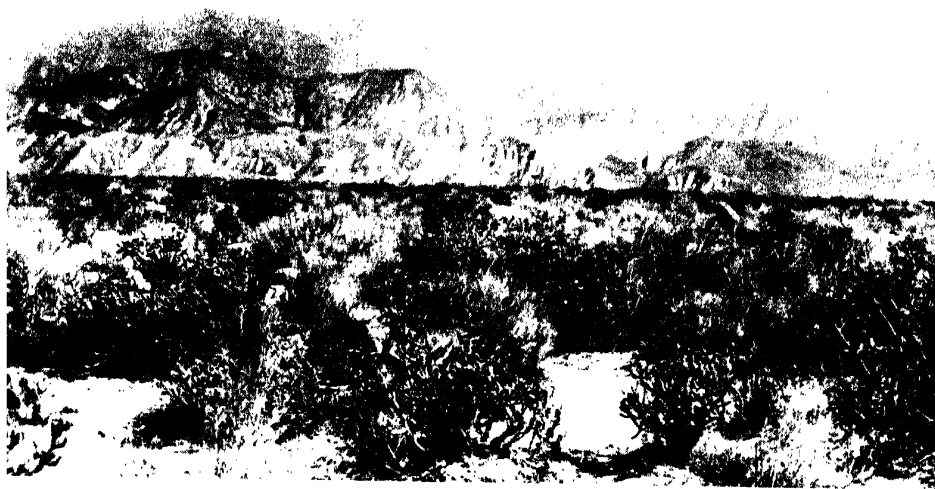
In addition to associated mountain groups due to interacting forces, such as folding, faulting, and erosion, mountains the origins of which have been only incidentally connected with each other sometimes are found in groups. In the southern part of the Rocky Mountain region, as in New Mexico and in westernmost Texas, volcanic cones are interspersed with mountains due primarily to diastrophism. The volcanic mountains of this area were formed at a much later time than the

of extreme folding, and folded mountains are accordingly modified in form by the effects of the faults. Overturned folds very frequently become thrust faults, as shown on page 281. Among the mountains which can be attributed to the joint action of these two forces are Chief Mountain, Montana (see page 280), and the Matterhorn; both consist of very ancient rock pushed over rock of younger formations. Thrust faulting on a vast scale has taken place in the Alps, great sheets of rock having been pushed horizontally northward over one another. Immense faults of this type are also known in many other parts of the world.

Fault, or block, mountains can be formed, however, in horizontal strata which have not otherwise been disturbed except for vertical elevation. Intersecting faults in a plateau can result in these mountains in several ways. Blocks of rock can be thrust upward to mountainous heights. The sinking of a number of blocks may leave certain others standing at a great height above their surroundings. Or blocks may be tilted, one edge rising as the opposite one sinks. Such a tilting or rotating movement was responsible for the present height of the Sierra Nevadas, as shown below. In this enormous fault a block 400 miles in length and 100 miles in width tilted westward. On the east edge of this block Mt. Whitney, the highest peak in the United States, looks down a precipitous east slope of more than 1000 feet to the mile; toward the west, however, the surface of the block descends



The Sierra Nevadas were the result of the tilting of a great earth block, giving the mountains a steep slope along the east-facing fault plane and a much more gradual western slope along the top of the block.



United States Forest Service

The San Bernardino range rises abruptly from the plain. These mountains are the dissected edge of a fault block.

gradually until covered by sediments washed into the central valley of California.

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associated ridges and peaks produced by folding and erosion. Glacial deposits often reach great thickness in the Alps, the Rocky Mountains, and elsewhere, but in such localities they are so dwarfed by their surroundings as to appear minor features of the topography. Deposits made by the wind are generally of little consequence in mountainous regions, although sand dunes in Colorado approach 1000 feet in height.

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XIII · VULCANISM



The term *vulcanism* denotes all activity of molten rock, whether above or below the surface. Its use arises from the name of Vulcan, the Roman god of fire, who was said in ancient times to maintain a workshop beneath the towering bulk of Mount Etna, on the eastern shores of Sicily. From the same source also is taken the word *volcano*, which is defined as an opening in the earth from which hot rocks are ejected.

Volcanic material which is forced out upon the surface of the earth is said to constitute an *extrusion*. It may be ejected by a volcano, or it may consist of lava which emerges from a fissure. Molten rock which is forced into the midst of other rocks but which solidifies without reaching the surface is described as an *intrusion*. The terms intrusion and extrusion are applied both to the structures thus formed and to the movements involved in their formation.

CAUSES OF VULCANISM

The ultimate cause of vulcanism is heat, but the details of the process present many perplexing problems. What is the source of this heat? What is the origin of the magmas, and of the steam and other gases contained in them? What causes their ascension to or toward the surface? The answers to these and other questions are not known with certainty, and inferences drawn with respect to them should be regarded as tentative.

The source of heat. Perhaps the most widely accepted interpretation of volcanic heat is that it is a part of the original heat of a once molten, or at least very hot, globe. But even if this be the case there is no reason why contributions of heat should not have resulted from gravitational compression, the friction developed when great blocks of rock slip upon one another, compression and friction involved in the folding of mountains, the energy evolved by the disintegration of radioactive minerals in the rocks, and chemical reactions. All such

sources have been urged as causes of vulcanism, but, with the probable exceptions of the "original heat" and radioactivity, each appears individually inadequate to produce the observed effects. Until more definite evidence is forthcoming, we may well assume the interaction of several of these heat sources.

Origin of magmas. Magmas, as we have seen from study of the igneous rocks, vary widely in composition, ranging from very siliceous to very basic. Nothing is known of the depth at which they originate. Basic lavas, especially those comprising flows or intrusions of great size, may be supposed to have arisen from the great reservoir of basaltic rock which underlies the continental platforms and the ocean basins. The rate of temperature increase with depth will hardly permit us to assign to the source of the lavas a depth of much less than twenty-five or thirty miles, except where great heat accumulates locally as a result of radioactivity, compression, or some such cause. Magmas of acidic composition, therefore, might be assumed to come from the melting of granite in the lower parts of the continental masses.

This view is in harmony with the fact that eruptions and intrusions on the continents may involve either acidic or basic magmas, the greater flows usually consisting of the latter, while eruptions beneath the oceans consist almost entirely of basalt. The behavior of some volcanoes, however, suggests that this explanation is entirely too simple to cover all cases. Closely associated volcanoes may erupt lavas of different kinds. Still more significant is the fact that some volcanoes (such as Lassen Peak) change the character of their eruptions, now disgorging acidic, now basic, lavas. From these and other considerations, it seems necessary to conclude that in many instances magmas undergo a separation of their constituents, a process known as *magma-tic segregation*. One of the important causes of this separation is the gravitational assortment of materials according to their weight, the heavier basic ingredients settling to the bottom of the mass, the lighter acidic portions rising to higher levels.

The complete independence exhibited by most volcanoes indicates that their lavas come from comparatively small reservoirs. It has been thought that some magmas may originate at relatively shallow depths from the effects of heat emitted by localized concentrations of radioactive minerals or other sources, followed by relief of pressure. Rocks

heated to above their normal melting points might be liquefied by the decrease of pressure resulting from deep erosion of the rocks above them, or by the lifting of the overburden by anticlinal folding. It is highly questionable whether sufficient relief of pressure to cause much melting could be brought about in such ways.

The movement of magmas. In lava flows and in volcanic eruptions of a quiet character the rise of magmas to the surface may be the result of pressures arising from the weight of overlying rocks. But lava is not always a passive agent, moving in response to outside forces; it often exerts great force of its own. Instead of being squeezed through pre-existing fissures, zones of weakness, and regions of lessened pressure, magma in many instances appears to blast its own way by means of forces residing within itself. Supporting this view is the existence of many intrusive structures that have been driven through formations with no apparent regard for differences in resistance; among these are a number of pipes several thousands of feet long in southern Germany, driven through solid sedimentary formations.

The source of the energy that drives the magma along, melting and forcing aside the rocks as it goes, is to be found in the expansive force of steam and minor quantities of other gases. These gases are kept in solution in the molten rock only because of the great pressure to which the rock is subjected, just as concentrations of carbon dioxide can be maintained under pressure in carbonated water. Upon the relief of pressure, steam separates from the magma and becomes an active agent in causing movement of the latter.

Steam is also the principal causative agent in explosive eruptions. Many violent eruptions follow periods of comparative quiescence, during which lava at the surface solidifies; the volcano may even appear extinct. Steam, however, may in such a case be forming beneath the surface, where it may accumulate in such quantity as to cause a terrific explosion.

When rock crystallizes in passing from the liquid to the solid state, the contained water is excluded from the crystals and is forced out in the form of steam, to mingle with the hardening lava. The volcano which quietly pours out lava, then, may be considered the young, vigorous one, while the explosive volcano may by dying, its violent disposition the result of steam emanating from its own crystallizing lavas.

The origin of volcanic gases. Like most of the subterranean phases of vulcanism, the origin of the gases present in magmas has long been a source of controversy. As already pointed out, the rocks themselves contain large quantities of water and water-forming minerals. Magmas obtain some of their water from this source, and some undoubtedly from their contacts with ground water; the relative importance of each of these sources cannot be determined with certainty. The fact that two thirds of all known volcanoes are in the sea or on sea islands has persuaded some observers that the steam of magmas has come from the seeping in of sea water; unfortunately for this theory the other third includes some nearly fatal examples. A consideration of the depths at which pressure must close all rock pores against the entrance of water seems to indicate quite conclusively that at the depths at which most magmas originate, the water present must be that which was originally in the rocks.

Of the gases present in ordinary magmas, steam usually comprises from 80 to almost 100 per cent. Second in abundance is carbon dioxide, which results principally from the inclusion of limestone in the molten mass.

TYPES OF ERUPTION

Some volcanic eruptions are violently explosive, while others are featured by a quiet outpouring of lava. Many examples of intermediate types are known, and the same volcano will not infrequently change from one type to another. The character of an eruption is governed chiefly by two factors: (1) the quantity of gases imprisoned within the molten rock and (2) the facility with which these gases can escape into the air. The latter factor depends upon the fluidity of the rock, which is determined both by its composition and its temperature.

Characteristics of lavas and magmas. The term *magma* is applied to molten rock which still resides beneath the surface of the earth, while *lava* denotes such material which has been extruded, either before or after its solidification. Magma and lava differ somewhat in composition, since exposure to the air allows the escape of some of the gases which are held in the magma under pressure. The conception of lava and magma as molten rock is a little too simple for some purposes; they are really solutions of minerals in other minerals. This

fact affects certain of their characteristics, such as their melting points, and the order in which their different constituents crystallize out.

As has already been pointed out in connection with igneous rocks, some lavas contain predominant quantities of silica, while others are chiefly of ferromagnesian composition. Those in which the silica content runs to 65 per cent or more are termed siliceous or acidic lavas, while those of which silica is a distinctly subordinate constituent are classified as basic or basaltic. Although basic lavas have higher melting points than those rich in silica, they are at corresponding temperatures much more fluid, and are therefore capable of flowing much greater distances before congealing. Slopes produced by this kind of lava, which is quite fluid at 2000° F., are likely to be very low, and in some cases are practically level. When poured out of a volcano these lavas may flow at the rate of ten or twelve miles an hour, soon slowing, as the mass cools, to a creep, which is said to continue in some cases for a matter of years. The siliceous lavas, on the other hand, are stiff and viscous at 3500° F., and rarely flow for more than a short distance.

In either kind of lava, fluidity of course increases with temperature. The temperatures of most lavas do not generally exceed 2000° F.

Quiet eruptions. Since basic lavas are generally more fluid than acidic ones, gases present during eruptions involving the former type are usually able to work their way out of the rock without causing great disturbance. A large amount of steam or other gases dissolved in a magma, while creating explosive possibilities, increases the fluidity of the mass, and may therefore contribute to the quietness of an eruption.

Another condition favoring eruptions of the quiet type is the occurrence of eruptions at fairly brief intervals, such as to prevent the freezing over of the surface lavas and consequent accumulation of steam.

Stromboli, the "lighthouse of the Mediterranean," is more or less continuously active. It is mildly explosive, but its lavas never become entirely solid, hence no eruption of extreme violence occurs. It may be considered an example of an intermediate type.

Explosive eruptions. Extrusions of siliceous lavas such as those giving rise to rhyolite are likely to be accompanied by explosions produced

by the impeded passage of steam outward through the rapidly hardening mass. This sort of eruption is especially likely to occur when an eruption (of either kind of lava) follows a long period of quiescence, during which a thick plug of rock has formed in the opening.

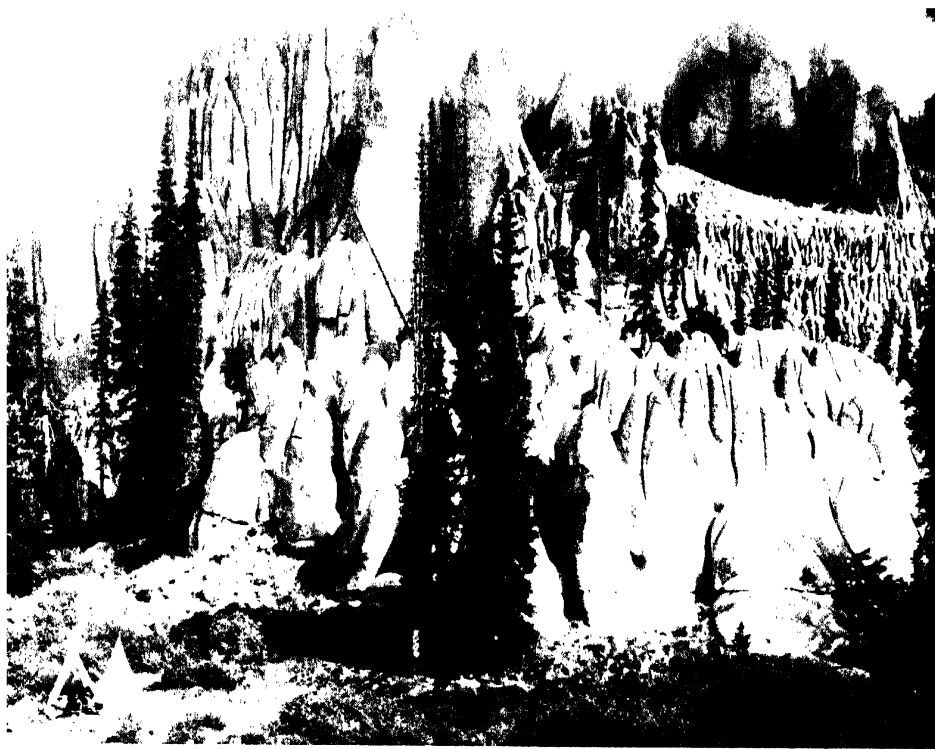
In some cases, the solidified lava plug in the vent of a volcano becomes so thick that imprisoned steam cannot blow it out, but instead tears a new opening through the sides of the mountain. The force of the explosion thus expends itself laterally, driving a dense black cloud of hot gases, dust, and larger fragments, some of them weighing many tons, outward at a high rate of speed. Such horizontal explosions constitute what are called *pelean* manifestations of vulcanism.

Fissure eruptions. One of the quieter forms of eruption is the issuance of lava from fissures, sometimes many miles in length. Many volcanic eruptions are accompanied by the flow of lava from cracks in the sides of the volcanoes. On a much vaster scale, lava flows have built up great plateaus in several parts of the world. The lavas concerned in these eruptions are usually, although not always, of basaltic composition; as a consequence they remain fluid for a long time,

National Park Service, photograph by Davidson



Volcanic blocks. Large, solid volcanic products generally point to a more or less lengthy period of quiescence between eruptions, during which steam and other volcanic gases have time to accumulate in great quantities. The result is likely to be an explosion of immense violence, blowing to bits the solid plug which has formed in the throat of the volcano. Blocks such as those shown in the illustration usually have sharp edges, showing that they were entirely solid when broken. Volcanic bombs do not show this characteristic, since they were still fluid when ejected.



United States Forest Service

"The Ghosts," of Wheeler National Monument, Colorado, are grotesquely eroded masses of volcanic tuff.

Lava flow, principally of the aa type.

National Park Service



spreading out horizontally for long distances. In Iceland lava is known to have flowed for sixty miles from its place of emergence from the ground.

Fissure eruptions provide the most impressive of all evidence of the power and importance of the volcanic forces residing within the earth. The vast basaltic flows of the Deccan region of India, the Columbia Plateau of parts of Washington, Oregon, and Idaho, and of Iceland have already been referred to. Rhyolite flows on a much smaller scale are known in South America, Africa, and Yellowstone Park.

PRODUCTS OF VULCANISM

Gases. The emission of gases is the first as well as the last manifestation of most volcanic eruptions, preceding the main eruption and continuing as emanations from the cooling lavas for a long period following it. Volcanic gases are of variable composition, differing from place to place and often changing in character during the course of the same eruption. Some of those most commonly present are steam, carbon dioxide, carbon monoxide, hydrogen, oxygen, nitrogen, hydrogen chloride, hydrogen sulfide, and sulfur dioxide.

In addition to the ordinary gases, volcanic emanations contain substances known as sublimates, which are gaseous only at high temperatures, and which condense directly into solids. Of these sulfur is the most common, being associated with practically all volcanoes, while salt, ammonium chloride, and a considerable number of other elements and compounds of this sort are sometimes present.

Pyroclastic materials. Materials which are blown out of a volcano in a fragmental condition are known as *pyroclastics*. These solid particles vary in size from microscopic dust to blocks a hundred feet in diameter. The finest particles constitute *volcanic dust*, while larger fragments, up to one quarter of an inch in diameter, are designated as *ash*; sometimes no distinction is made between these classes of particles. Volcanic dust may remain in the air for years following a vigorous eruption, and it is sometimes carried in large quantities far from its point of origin. In 1783 dust was blown from Iceland to Scotland, a distance of six hundred miles, falling in such quantity as to kill growing crops. Thick deposits of volcanic dust are known in Nebraska,

Pahoehoe lava, Craters of the Moon National Monument, Idaho. Even in its solidified state, it is easy to see that this lava once possessed great fluidity. Some fluid lavas have been known to flow at speeds of more than 10 miles an hour. These fluid lavas, being thoroughly mixed with gaseous vapors, do not block the vents of the volcano and are therefore associated with quiet eruptions.



National Park Service

Kansas, and Oklahoma; these are supposed to have originated in volcanic explosions in the Rocky Mountains, four or five hundred miles distant.

Volcanic fragments ranging in size from one fourth of an inch to one and one-half inches are classified as *lapilli* or *cinders*. These particles are often porous, as a result of the expansion of gases within them while in a semisolid condition. Masses larger than cinders, if solid when ejected, are called *blocks* (illustration, p. 292). These result from the breaking up of a hardened lava crust. Stromboli hurled solid masses weighing 30 tons a distance of two miles during an eruption in 1929, while Cotopaxi, in Ecuador, is credited with the stupendous feat of throwing a two-hundred-ton block nine miles from the volcano.

Bombs are masses which are liquid when ejected, solidifying in the air. They form oval, spindle-shaped, or irregular structures of all sizes.

Rock formed by the consolidation of volcanic dust or ash is called *tuff*; that composed of coarser fragments is *volcanic breccia* or *agglomerate*. Such rocks may form deposits thousands of feet in thickness. The finer particles are frequently picked up and deposited by water, in which case they show stratification, and may be considered intermediate between igneous and sedimentary rocks.

Solidified lavas. The forms assumed by a solidifying lava vary according to its consistency, gas content, and the strains to which it is subjected. Fluid lavas may develop a ropy or billowy surface known

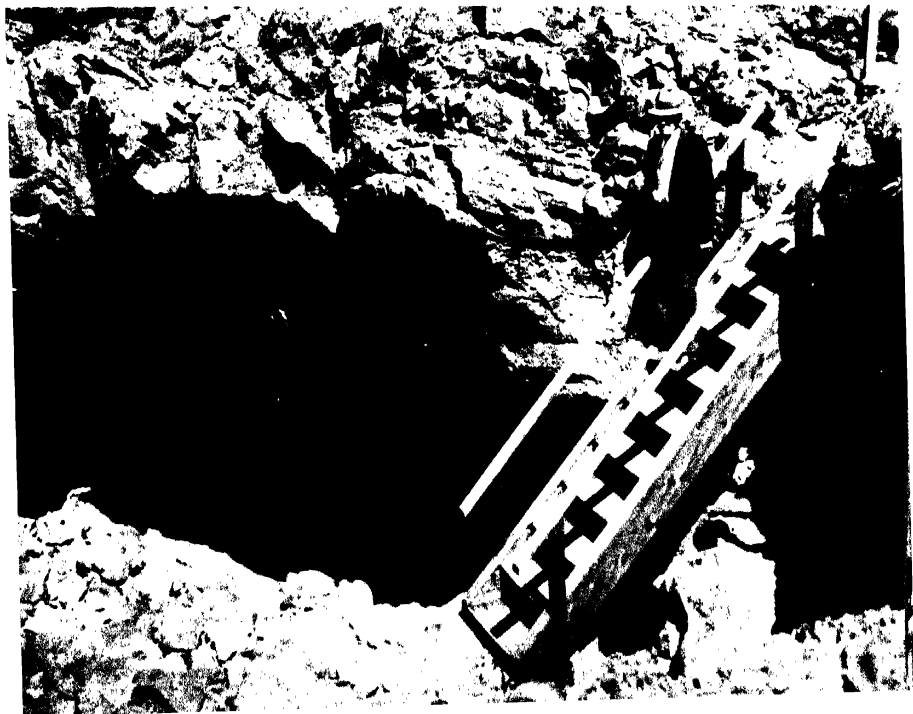


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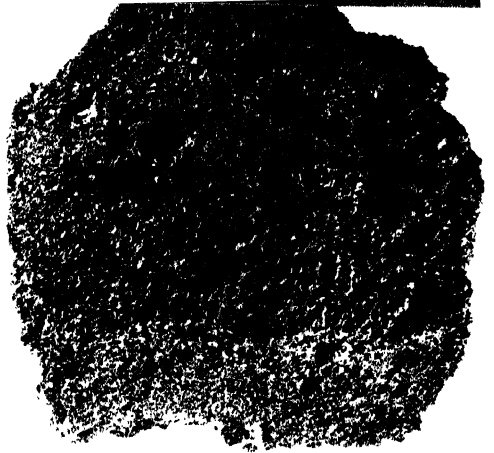
*Fragmental volcanic material floated into present position on a lava flow.
Craters of the Moon National Monument.*

*Cavern formed in lava by the draining off of the still-molten rock beneath a
solidified surface crust.*

National Park Service, Union Pacific Railroad Photograph



Scoria, a rough, vesicular basalt, is formed at the surface of lava flows by the escape of the gases from the thickening mass, producing a porous texture. Some specimens contain so much pore space that they will float on water. Lava of this kind is associated both with lava flows and with extinct volcanoes, in which it may have formed without escaping.



Ward's Natural Science Establishment, Inc.

from the Hawaiian as *pahoehoe*. This type of flow is well exemplified in the Craters of the Moon district of Idaho. Thick lava flows often solidify on the surface, while remaining in a liquid condition below. Flowage of the underlying liquid lava breaks the surface rock into rough blocks of all sizes which may be dragged along with the current and heaped into extremely jagged and disordered masses; lava of this kind is known as *aa*. (Illustrations, pp. 293 and 296.) Another effect of the persistence of fluid lava beneath a hardened crust is the occasional formation of caves, an example of which is shown in the illustration on page 296. Portions of the molten rock drain away, leaving a solid roof above the cavity thus formed.

Lavas erupted beneath the surface of the sea or of lakes, or flowing into bodies of water from the land, may assume an unusual structure resembling pillows neatly fitted together. This structure is the result of the formation of many curving joints, the origin of which is not thoroughly understood. Such lavas are known as *pillow lavas*.

The finer structure of lavas may show much variety. Lavas are not usually entirely homogeneous, but exhibit diversities caused by cavities, differences of composition, or areas of different colors. The movement of the cooling mass drags these features out into layers, giving the hardened rock a banded appearance.

Viscous lavas frequently solidify so rapidly that volcanic glass, known as *obsidian*, forms either upon the upper surface or where the base of a flow comes in contact with cooler rock. This rock is illustrated on page 378. *Pumice* is a solidified rock froth or foam, nearly always of siliceous composition. It forms on the surface of a seething mass of lava from which bubbles of gas are seeking escape; the ex-

pansion of this gas produces so many small pores in the resulting rock that it will float on water. Pumice does not have the glassy appearance of obsidian, because of the air contained within its pores, but it is nevertheless a glassy, noncrystalline rock. The expansion of gases rising to the surface of basaltic lavas produces a porous rock of a much coarser character known as *scoria*, which is shown in the illustration on page 297. This is a dark or definitely colored, finely crystalline rock in which the pores are usually considerably larger than those of pumice. Structure of this kind is described as *scoriaceous*.

During the formation of obsidian, imprisoned gases may keep small sections of the siliceous lava in a sufficiently fluid state to allow crystallization to take place. The result is the presence in the glass of rounded masses of crystalline feldspar, known as *spherulites*.

Rising bubbles of steam occasionally leave tubular trails in basaltic lava. If the lava is still flowing, these narrow tubules are bent in the direction of movement.

Distension of molten rock by steam or other gases often produces elliptical cavities. Mineral matter, usually silica, may later be deposited in these openings, forming almond-shaped nodules called *amygdules*. Agate is sometimes formed in this way.

VOLCANOES

Volcanic cones. Some of the world's loftiest mountains are cones built up by volcanoes. On the other hand, some volcanoes have no cones at all; these have blasted openings through the surface rocks with but little extrusion of molten matter, leaving only open pits surrounded by scattered rock fragments. Between these extremes are to be found examples of volcanic structures of many sizes and shapes.

Explosive volcanoes nearly always construct cones of pyroclastic materials around their outlets. Volcanic dust and ash are drifted by wind or washed by rains away from the orifice of the volcano, forming slopes that lie at low angles. Coarser materials fall nearer the opening, where they lie at high angles, sometimes 30° or more, though they seldom form elevations of very great height. These structures, usually called *cinder cones*, are in many instances the product of a single eruption. Note the several small cones shown in the photograph on page 316.

Mount Capulin, a wonderfully symmetrical cinder cone of northeastern New Mexico, rises sharply above the plain. Its flanks consist largely of small fragmental material. At the bottom of its well-preserved crater lie great volcanic blocks. On the whole, Mount Capulin tells a story of diminishing activity, probably culminating in a violent explosion which may have occurred no more than 2000 years ago.



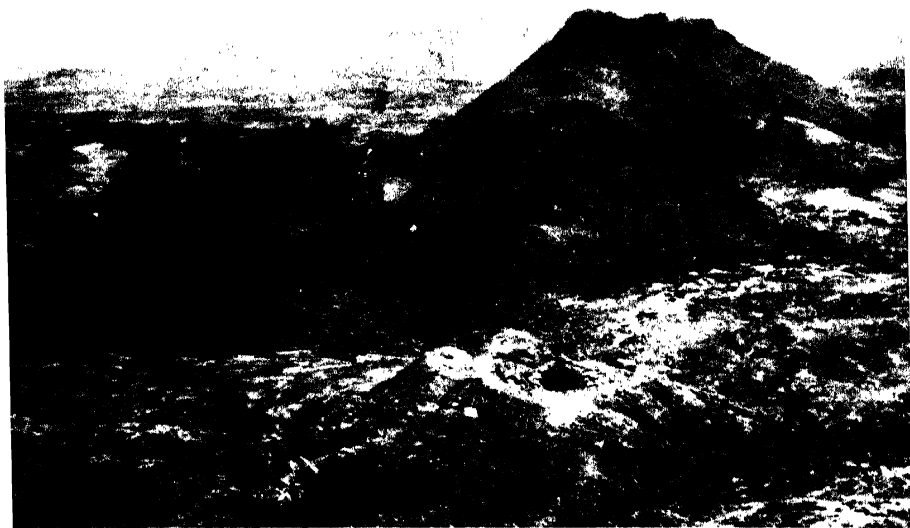
National Park Service

Spatter cones are small piles of pyroclastic matter ejected from solidifying lavas by escaping gases. They occasionally form along cracks in the hardening surfaces of lava flows. Several of these structures are illustrated on page 300.

In contrast to the steep slopes formed by pyroclastic cones, mountains resulting from lava flows usually have gently sloping sides. These may be of great height and cover large areas, but their slopes, if the result of flows of highly fluid lavas, may lie at inclinations of 10° or less. Because of their rounded, flattened shape, mountains of this kind are designated as *shield volcanoes*. If the lava emerging from a volcanic vent is very viscous, it may not flow, but accumulate in the form of a *plug*.

The majority of volcanoes do not belong definitely to any of these types, but show mixed characteristics, being constructed partly of pyroclastic materials and partly of the hardened products of lava flows. Repeated explosions may erupt fragments of differing sizes and kinds; these, alternating with occasional lava flows, form rough layers, which dip away from the volcano, except near the center, where they sometimes dip inward. The layered structure of its materials identifies this sort of mountain as a *strato-volcano*.

Strato-volcanoes include some of the largest, as well as most majestic and symmetrical, of mountains. Loose cinders and blocks are protected from destructive agencies by the lava flows which from time to time cover them, and the entire structure is strengthened by lava which bursts from the basal portions of the central vent into radiating



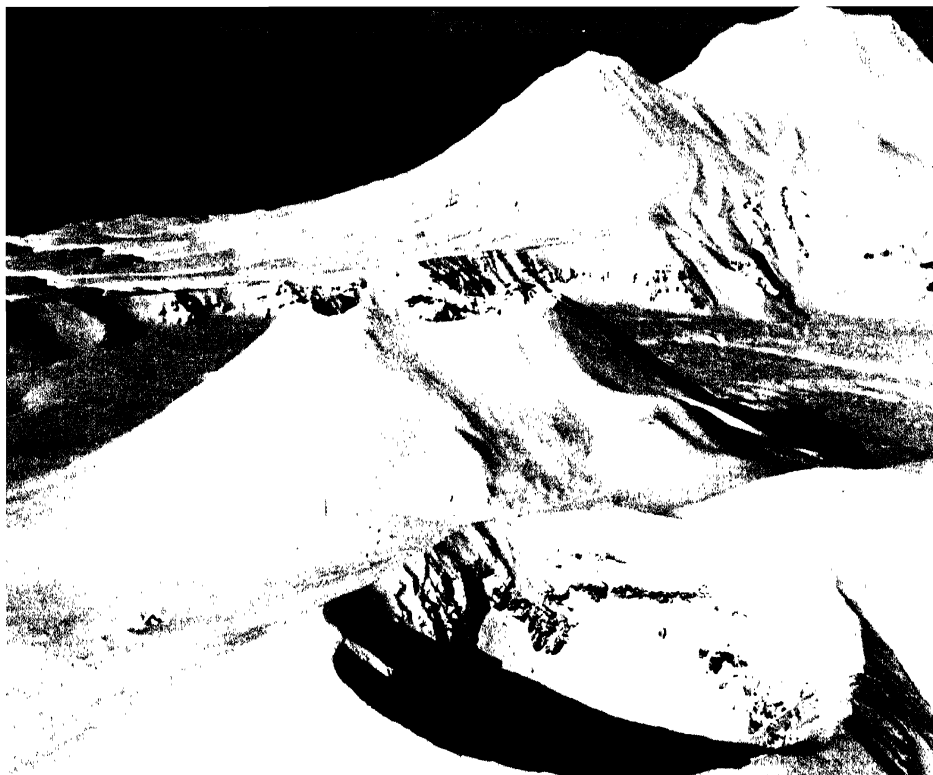
Photograph by H. E. Brown

Spatter cones of the Craters of the Moon district, Idaho.

Mayon, a superb strato-volcano of the Philippines.

Geological Survey, Republic of the Philippines





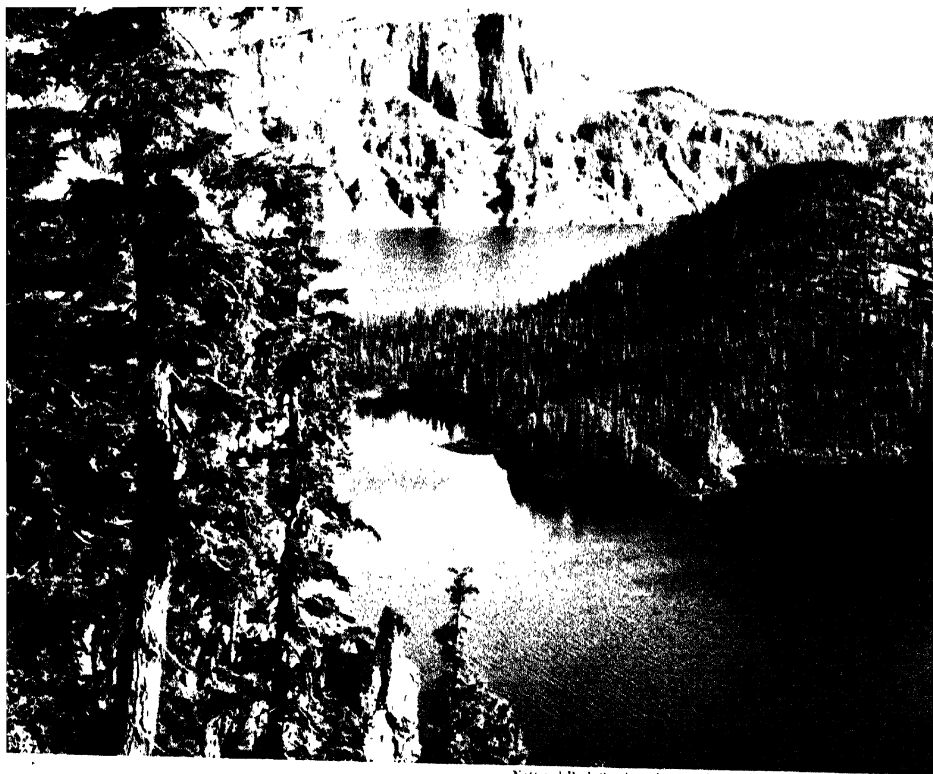
Official United States Navy Photograph

Twin craters of an Aleutian volcano.

fissures. Lava forces its way through the walls of the lower parts of the cone more often than it rises and overflows the top, especially if the volcano has grown to a considerable height; for this reason, the lower slopes of a strato-volcano are frequently more gentle than those of its summit, which may consist of steeply-dipping accumulations of cinders. Mayon, in the Philippines, is often cited as a perfect example of this type of volcano; the symmetry of this mountain may be seen in the illustration on page 300. Fujiyama, southwest of Tokyo, is another excellent example.

Craters and calderas. The external opening through which volcanic material is ejected is called a *crater*. This opening extends downward into a narrowing aperture known as the *throat* of the volcano. Large craters sometimes contain secondary cones, each with a crater of its own, within them.

The country rock surrounding a volcanic crater remains for the



National Park Service, photograph by George A. Grant

Crater Lake, occupying a great caldera of the Cascades in Oregon. Wizard Island is a cinder cone formed by an eruption subsequent to the formation of the caldera.

most part undisturbed. Adjacent rocks may, however, be bowed upward by the force of volcanic extrusions; in some cases they even sag inward toward the opening.

Openings of great size, especially if they are of large area in relation to their depth, are known as *calderas*. The exact significance of this term varies somewhat in geological literature. Some authorities limit the term to pits resulting from the collapse of the upper part of a volcanic cone, the material sinking into the molten matter below, or into a cavity left by the draining out of the magma. Others designate an opening formed in this way as a *volcanic sink*, reserving the name *caldera* for depressions resulting from such extremely violent explosions as destroy most or all of the pre-existent mountain.

An outstanding example of a caldera is the basin occupied by Crater Lake in southern Oregon (see illustration above). This pit is five or more miles in diameter, and enclosed by cliffs rising 2500 to 4000 feet

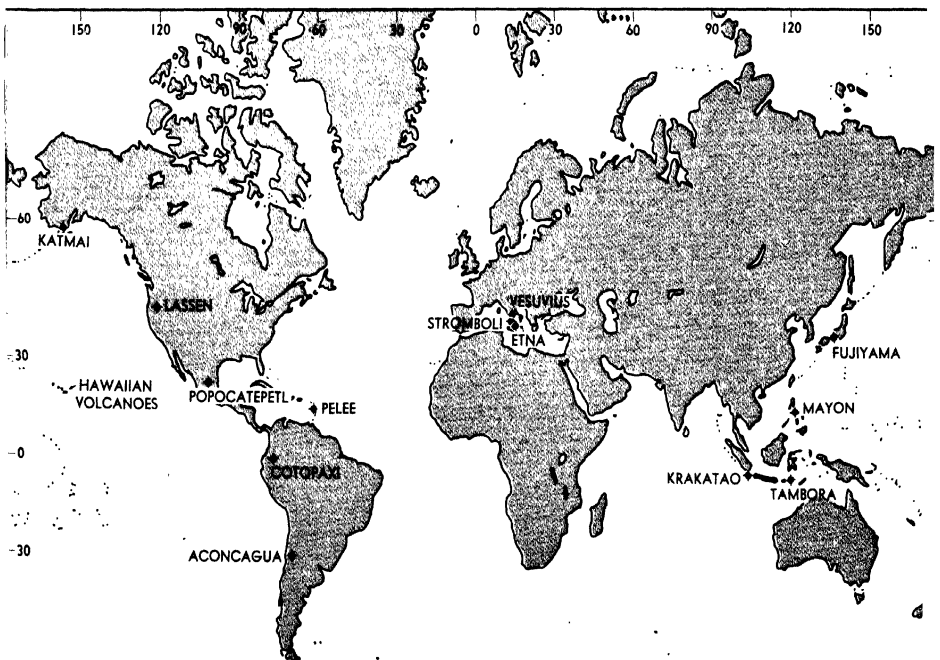
above its bottom. The general belief is that this immense basin was formed through the in-sinking of some fifteen cubic miles of rock; however, there is evidence that the volcano which once occupied the site of Crater Lake was at one time extraordinarily explosive, and some geologists believe that the caldera resulted when its top was blown off. The map on page 438 shows the details of this great crater.

Other calderas are those of Kilauea, on the island of Hawaii, and of Ngoro, in East Africa; the latter is perhaps the world's largest caldera, measuring twelve miles across and 2000 feet in depth.

Number and distribution of volcanoes. Something more than five hundred volcanoes are known to have been in active eruption since the beginning of historic times. Several thousand more have been active in recent geological times, and many of these may still be in a dormant rather than an extinct state.

Volcanoes that have been recently active show a decided preference for positions in or near the sea. Especially striking is their distribution around the Pacific Ocean, where they form a veritable "ring of fire." Beginning in Tierra del Fuego, this belt extends through the Andes region, along the western coast of Central America, and into Mexico. From central Mexico to Alaska, a distance of about 4000 miles, there

The location of some of the world's greatest volcanoes.



is but one active volcano, but this region presents abundant evidence that volcanic activity was in progress on a grand scale at no very distant date. In Alaska and through the Aleutian Islands the chain of volcanoes continues to the coast of Asia and southward through Kamchatka, Japan, the Philippine Islands, East Indies, and New Zealand.

Except in Central America, not one active volcano is to be found upon the Atlantic coast of any continent; but another belt includes numerous Atlantic islands, extending southward from Iceland through the Azores, Canary Islands, Cape Verde Islands, Ascension, St. Helena, and Tristan da Cunha. Two of the most intensely volcanic regions of the earth include the West Indies, Central America, southern Mexico, and the northern section of South America, and a district on the other side of the Pacific including the East Indies and the Philippines. Among other important volcanic localities are the Mediterranean region and East Africa.

A few volcanoes, such as those of Africa, are situated far from any ocean; but these are rare exceptions. In geological times past, however, considerable volcanic activity occurred on the interior of continents—in Utah, Idaho, New Mexico, and Colorado, for example—some of it a thousand miles from any seacoast.

Many volcanoes show a tendency to arrange themselves along short curving lines that often bend out toward the sea. Noteworthy examples are to be found among the volcanoes of Alaska and eastern Asia. Among the volcanic islands of the Pacific numerous cases of linear arrangement present themselves, frequently exhibiting a northwest-southeast trend; the Hawaiians and the volcanoes of the island of Bali are among the more conspicuous examples. This linear arrangement suggests that some volcanoes have probably arisen along cracks, or at least along seams of weakness, in the crust. That such a weakness is not necessarily prerequisite to the development of a volcano is, however, obvious; for we have numerous examples of volcanoes which have burst through the crust at points where it gives no indication of thinness or weakness. Pirsson and Schuchert point out that volcanoes in the Grand Canyon region did not appear *within* the Canyon where the crust had been eroded away to a depth of a mile or more, but on the sides, lava running down into the chasm.

Nevertheless, the significance of the general arrangement of vol-

canoes is clear; the young mountains, earthquakes, and recently active volcanoes have the same general distribution, a distribution that must correspond to weak regions of the crust or to regions which have recently been acted upon strongly by forces residing within the earth.

The life history of volcanoes. Several volcanoes have originated during historic times. In 1831 an eruption south of Sicily built an eminence known as Graham Island, which had a circumference of about three miles and a height of 200 feet above the Mediterranean. This single eruption seems to have ended the life of the volcano, and the island which resulted from it was destroyed by the waves within three months' time.

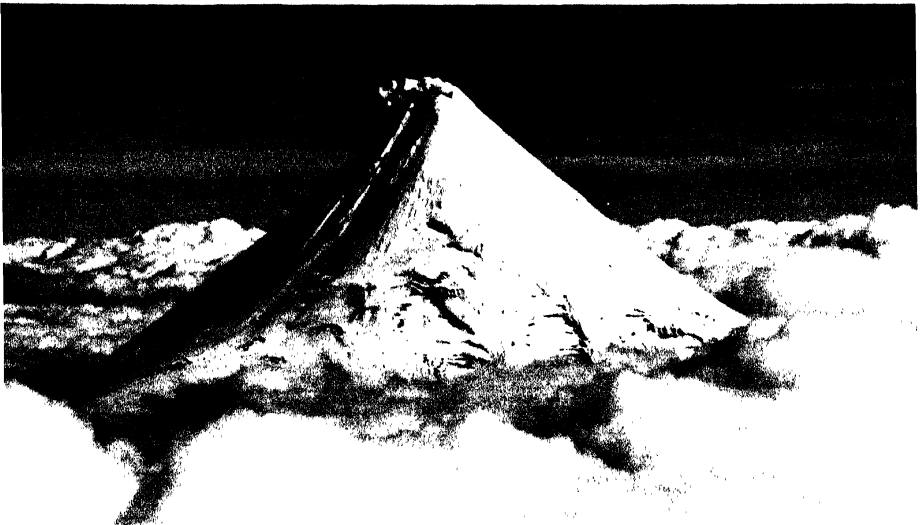
A number of new volcanoes have appeared within the past two centuries in Mexico and Central America. Jorullo, 170 miles southwest of Mexico City, erupted for the first time in 1759. Two new volcanoes have appeared in San Salvador, of which one, Izalco, now nearly 3000 feet high, is still active. The most recent of all new eruptions was that of Parícutin, situated in the same general section as Jorullo. This volcano was born early in 1943, and is still growing vigorously.

While these and other "new" volcanoes have come into existence during the very brief period of human history, it is worth noting that all of them are located in zones of volcanic activity. No eruption is known to have occurred in a nonvolcanic region within recent times.

During the active span of life of a volcano, its extrusive forces

The smoldering peak of Mt. Shishaldin, Alaska, protrudes through the clouds.

Official United States Navy Photograph





United States Geological Survey, photograph by H. E. Gregory

Agathla, a great volcanic neck, is impressive even in monument-dotted Arizona. This towering volcanic remnant rises abruptly 1225 feet above the surrounding plain. It exhibits the cylindrical form and precipitous sides typical of such structures. The actual cone of the volcano, being less resistant, has been eroded away, leaving only the hardened material which once filled the volcanic vent or throat, forming a hard core or neck. Eventually this will be worn down and even the roots of the volcano will disappear.

generally more than keep pace with those which tend to wear it down, and its cone expands in size. Even after eruptions have ceased, a volcanic cone may exhibit surprising resistance to erosion. Although finer particles of pyroclastic matter are washed down the slopes, the porous character of the coarser materials permits a large part of the rain which falls upon them to sink within without exerting marked erosional effects.

After discharges of lava or fragmental material have come to an end, a volcano often continues to give off gaseous emanations for a long time. This is illustrated by the picture of Mt. Shishaldin on page 305. Sulfurous fumes may be given off in considerable quantity for a time, followed at last by carbon dioxide, the "dying gasp of the volcano." Geysers and hot springs may be the final indications of the volcanic character of a region. Examples of volcanoes in all states of declining activity could be cited in the United States, from peaks of the Cascades which are exhaling sulfur fumes to the hot springs of the Yellowstone district.

Eventually the volcano, like any other mountain or other eminence, falls prey to erosion. Gullies and ravines appear on its sides, and little by little cinders and lava are torn loose and washed away. The last visible sign of the cone may be the plug of hardened lava which occupied the volcano's throat; this plug, being of superior resistance, may rise above the surrounding country for a long period. It is known

as a *volcanic neck*. From it may extend one or a number of lava ridges, formed by the filling of fissures which appeared in the cone during eruptions. Many volcanic necks have been recognized in Arizona, New Mexico, and other western states, of which Shiprock, in northwestern New Mexico, is one of the best known. Shiprock is pictured below. Page 306 carries an illustration of Agathla, a volcanic neck in northern Arizona.

IMPORTANT VOLCANIC ERUPTIONS

The following examples will illustrate many of the characteristics of vulcanism which have been mentioned.

The Hawaiian volcanoes. The Hawaiian group of islands consists almost entirely of basaltic lava which has issued from the bed of the ocean; with the exception of Iceland, it constitutes the largest isolated mass of volcanic material on the earth today. These islands are stretched out along a slightly curved line; they are, indeed, the peaks of an enormous submarine volcanic ridge which rises from a depth of 18,000 feet. The easternmost and largest island, Hawaii, is the only one known to possess active volcanoes at the present time, although

Shiprock, a majestic volcanic neck in northwestern New Mexico. It rises 1640 feet above the plane. Note the dike extending toward the left.

New Mexico State Highway Department





United States Geological Survey, photograph by Stear

The eruption of Kilauea on May 22, 1924—one of the two explosive eruptions which have occurred on the Hawaiian Islands during historic times. The same volcano erupted violently in 1790. Kilauea has the largest and most spectacularly active crater of any active volcano. The crater measures about three miles by two miles, exceeding in circumference that of the larger Mauna Loa by some four miles. During most of historic time, the volcano's activity has been chiefly confined to the deep oval pit (Halemaumau) at the bottom of the crater, but flows occasionally spread over the entire floor. Although some lives have been lost through eruptions of the Hawaiian volcanoes, most of these eruptions have done but little damage because they occur in sparsely populated country. Since 1911 a volcanic observatory has been maintained at Kilauea.

the nearby island of Maui contains the 10,000-foot volcano Haleakala, which may not be extinct.

Of the five large volcanic cones which dominate the island of Hawaii, only two, Mauna Loa and Kilauea, are considered to be active. Mauna Loa is the world's largest volcano; indeed, its largest mountain, from the standpoint of volume. It rises nearly 14,000 feet above sea level, and fully 30,000 feet above the sea bottom; it is some 60 miles in diameter, with a girth approaching 200 miles. All this immense bulk has been built up by intermittent lava flows. Kilauea is a smaller mountain, about 4000 feet high, on the flank of Mauna Loa and about twenty miles from the latter's summit. In spite of their close spatial association these two volcanoes are entirely independent in their action.

Although explosive eruptions by these volcanoes are not unknown,

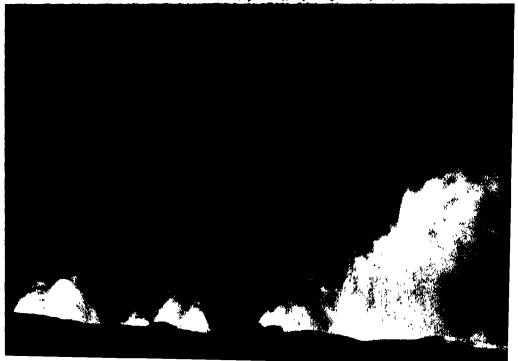
their activities are confined almost entirely to lava extrusions of the quiet type. The lava, being basic, is very fluid, which accounts for the low slopes of Mauna Loa, which average only about seven degrees. In the nearly flat summit of this volcano is a great crater, two to three miles in diameter. Preceding an eruption there usually appears in the crater a lake of red-hot lava, which bubbles and boils as steam pours upward through it. Fountains of glowing lava are thrown hundreds of feet into the air. Following these premonitory signs, the lava rises upward in the crater. During historic times the lava has never reached the summit of the mountain; before that point is reached, its weight cracks the walls of the crater. Through the fissures thus formed, liquid rock spurts several hundred to a thousand feet into the air, falling to form an incandescent river, which is sometimes one-half mile wide and fifty miles long.

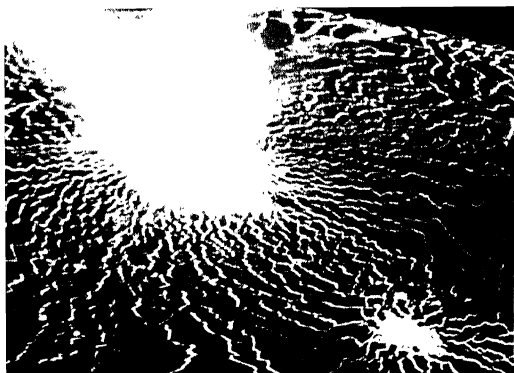
Near its source this lava stream sometimes moves faster than a man could run. But as it cools its pace slows. Traveling but a few feet per minute, its upper surface becomes covered with a mass of jagged, broken blocks of solidified material urged onward by the creeping motion of the still viscous lava beneath. The relatively cool solid fragments are rolled down the advancing front of the flow, and are passed over by the liquid parts. In 1926 the village of Hoopuloa, at the edge of the sea, was overwhelmed and completely destroyed by a lava flow thirty feet high. Hilo, the capital of Hawaii, was threatened with destruction in 1880-1881, when a lava flow emerged from a fissure in the flanks of the volcano, advancing steadily for six months and then stopping just outside the city. Again in 1935 a stream of molten rock started directly for Hilo, traveling from one to two miles per day. This time United States Navy bombers dropped explosives in the path of the lava, blasting out cavities in the mountain side in such a manner that the course of the flow was changed.

Mauna Loa has well been called "the monarch of modern volcanoes."

Kilauea volcano, Hawaii. Fountains of glowing lava leap 300 to 500 feet into the air, providing one of the most fascinating sights in the whole world. The area including Kilauea and Mauna Loa and other adjoining sections has been made into the Hawaiian National Park.

Hawaii National Park, photograph by Wingate





Hawaii National Park

The incandescent lava lake, Halemaumau, in the caldera of Kilauea volcano. It occupies a depression 3500 feet long by 3000 feet wide lying in the crater's floor, 1000 feet below the summit of the mountain.

The great caldera of Kilauea has been the scene of two violent eruptions during historic times. Its floor is a vast expanse of solid black rock containing a lake of liquid lava, Halemaumau, the "House of Everlasting Fire." When in a state of activity, Halemaumau exhibits an extraordinary degree of commotion, seething, foaming, spewing into the air. Most eruptions follow the pattern of those of Mauna Loa, a rise of lava which finally breaks through its confining walls to run down the slopes of the mountain.

J. D. Dana reports that the light emitted by Kilauea on one occasion was sufficient to permit the reading of fine print at midnight forty miles away.

Photographs of different phases of activity by Kilauea are reproduced on pages 308, 309, and above.

The Hawaiian volcanoes, both active and extinct, have produced typical examples of aa and pahoehoe. Successive lava flows often exhibit distinctly different colors, and minor cones of black, red, or orange materials may exist side by side. Pele's hair is one of the especially curious features of Hawaiian eruptions; this is a glassy, hair-like substance produced by wind action upon the rough surfaces of exposed lava or upon drops of lava in the air.

East Indian eruptions. The volcanoes of the East Indies are among the most vicious of the globe. In 1815 Tambora, on Sumbawa Island, exploded in a terrific eruption which was probably the most violent of any in all recorded history. The volcano scattered its substance, many cubic miles of it, over a vast area, burying villages and causing an appalling loss of life. Unfortunately, good scientific records of the details of this eruption are lacking.



The Italian Government

Historic Vesuvius, encircled by the shell of Mt. Somma.

An ocean of lava from Mt. Vesuvius engulfs San Sebastiano, March 25, 1944.

Official United States Navy Photograph



Hardly second to the explosion of Tambora, if not actually exceeding it in violence, was that of Krakatao,¹ a 2600-foot volcano on a small island lying between Java and Sumatra, a thousand miles west of Tambora. Not since 1680 had Krakatao shown signs of life. But in May, 1883, a cloud of steam was seen hanging over the mountain. During the following three months the region experienced a series of explosions and small earthquakes, culminating in the latter part of August in an eruption of unimaginable fury. The mountain was torn in two, and dust and ash driven seventeen miles into the air. The noise produced by this explosion was heard 3000 miles away; windows were broken at Batavia, Java, about one hundred miles distant, by the air wave that was generated. Volcanic dust totally darkened the sun over a vast area; some of this dust remained in the atmosphere for years, producing magnificently colored sunsets in distant parts of the world.

When the eruption of Krakatao was over, it was found that two thirds of the island on which it had occurred had disappeared. At first it was thought that the disruption of the island had been due directly to the explosion, but subsequent investigation indicates that its disappearance was due chiefly to its sinking into an enormous submarine caldera.

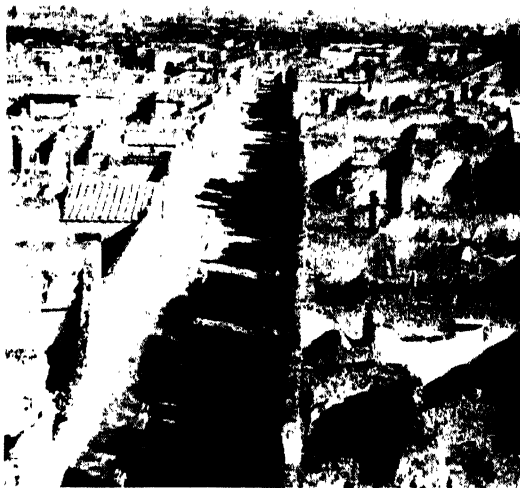
As the island of Krakatao was uninhabited, the loss of life in the immediate vicinity was small. However, the explosion generated great sea waves, some of them more than 100 feet high. These destroyed many seacoast villages and drowned 36,000 people.

Vesuvius. Seven miles from the city of Naples there stood at the beginning of the Christian Era a great mountain known to the Romans as Mt. Somma. Verdure-covered for untold centuries, all remembrance of its treacherous nature had faded from the minds and traditions of men. Flourishing and brilliant cities sparkled near its base, and its slopes provided unusually fertile soil for vineyards and fruit orchards.

In the year 63 A.D. the city of Pompeii, a fashionable resort of many wealthy Romans, suffered a severe earthquake. Earthquakes were not uncommon in that section, and the citizens set to work to rebuild their villas, temples, and shops. Other quakes followed during the next

¹Strictly speaking, *Krakatao* is the name of the island on which the catastrophe occurred. The volcano was called *Rakata*, but this usage is rarely employed today.

Disinterred Pompeii. Buried by the awful catastrophe which overwhelmed it in 79 A.D., the city lay for centuries under twenty feet of volcanic ash, pumice, and earth. It was discovered by accident in comparatively recent times and almost one half of it has now been excavated. The reason it remained unknown for so long is that eruptions of Vesuvius covered the original coast line, concealing its position.



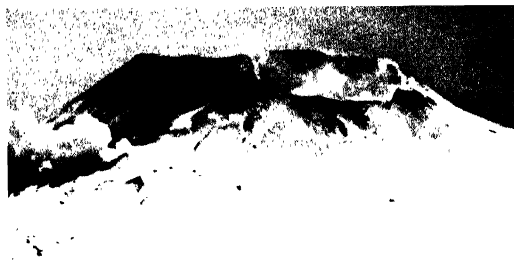
The Italian Government

several years, and in the year 79 Mt. Somma exploded, tearing away a large part of its cone and dropping an avalanche of fragmental rock upon the surrounding countryside.

The younger Pliny, who was residing at the time at Misenum, eighteen miles from the volcano, described the disaster graphically in a letter to the historian Tacitus. Even at that distance, he relates, the falling ash and cinders darkened the sky, "not with the darkness of a cloudy, moonless night, but with that of a closed room with the light extinguished." Most of the people imagined "that the last and eternal night was come which was to destroy the gods and the world together."

Pompeii was buried under twenty or thirty feet of volcanic dust and stones. In the space of a few hours the everyday activities of the people were cut off and preserved in such a way as to give recent generations valuable insight into the life of those times. Pictures on the walls are still in fairly good condition. Food remained on tables. Even molds of the bodies of people and of their domestic animals have been found and filled with plaster, preserving, in some cases, expressions of terror upon the faces of persons trapped within the city. Most of the people, however, appear to have had ample time to escape.

Herculaneum, even nearer the mountain than Pompeii, suffered an equally complete destruction. The condensation of steam emitted by the volcano produced heavy rains, which washed dust and ash down



Mount Etna, on the island of Sicily, is the highest mountain in Italy and the largest active volcano in Europe. Rising out of deep sea water to a height of 10,875 feet, with a base circumference of over 90 miles, Mount Etna is one of the most active and destructive of all volcanoes. Loss of life through its eruptions has run into many thousands.

The Italian Government

the slopes of the mountain in torrents, cementing cinders and blocks which had fallen upon the city into a solid rock.

After the eruption some of the citizens returned to the site of Pompeii, dug shafts and tunnels into the material covering their city, and in that way removed some of their valuable articles. But gradually men forgot the tragedy of Pompeii and Herculaneum; new villages were built above them, only to be destroyed in their turn by an eruption in 472. At last even the locations of the ancient cities were forgotten, and for fifteen hundred years their sites remained unmolested, being finally discovered through the excavation of an aqueduct.

The eruption of Mt. Somma in the year 79 was entirely of the explosive type. Numerous subsequent eruptions have occurred, all of the same type up to that of 1066, at which time lava was ejected. A very destructive eruption of both lava and fragments took place in 1631, after nearly a century and a half of quiescence. Following this eruption, the volcano underwent a change of character, remaining in a state of almost constant mild activity, but given to recurrent periods of violent outbursts. One of its most violent eruptions was in 1906. Its most recent period of marked activity was in 1944, when considerable damage was done to property.

The cone known as Vesuvius has been built near the center of the semicircular rim that is all that remains of Mt. Somma. Vesuvius is about 4000 feet in height, a little taller than Somma. Page 311 carries photographs showing recent activity on the part of Vesuvius, while the photograph on page 313 shows a portion of Pompeii, giving an idea of the scope of the disaster of 79 A.D.

Other active Mediterranean volcanoes. Far larger than Vesuvius is Mt. Etna, on the eastern shore of Sicily. Rising nearly 11,000 feet high, with a diameter of 30 miles and an area of 460 square miles, it is the greatest volcano of Europe. The mountain has been the product of successive lava flows. Its lower slopes are gentle, and intensively cultivated. At its summit is a cinder cone 1000 feet high. Around the base are about 200 subsidiary cones, situated along fissures radiating from the central vent.

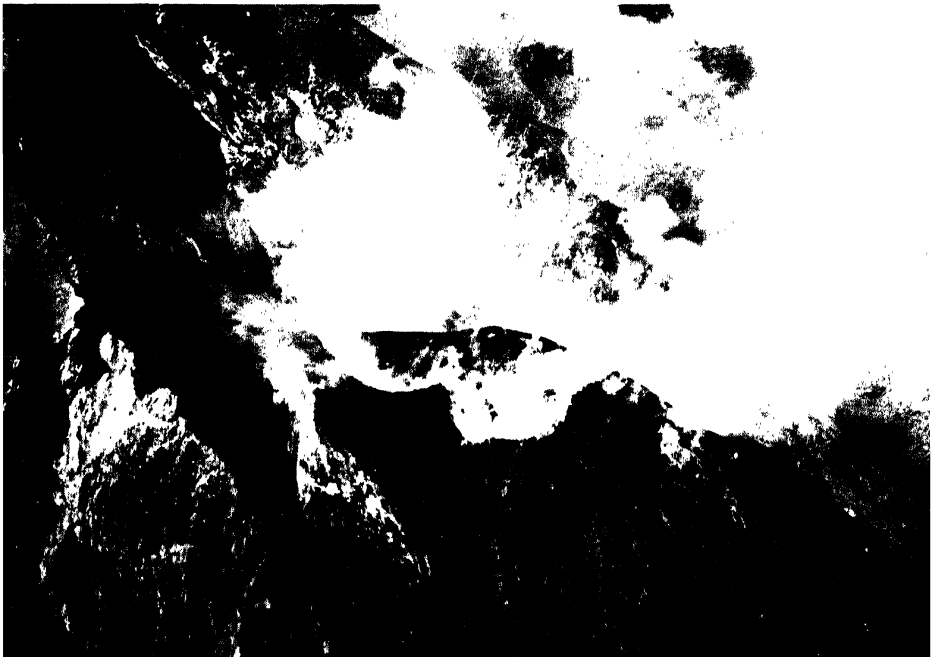
Mt. Etna has been active since prehistoric times, the earliest recorded eruption having taken place during the eighth century B.C. Many serious and sometimes destructive eruptions have occurred since (see photograph, p. 314).

Stromboli, one of the volcanic islands making up the Lipari group, north of Sicily, has been mentioned as an example of a volcano in continuous, moderate activity. It rises abruptly from the sea to a height of 3000 feet. Like Etna, it has been active since the dawn of history. It is reproduced in the photograph on this page.

Another of the Lipari volcanoes is Vulcano, which is fitfully explosive, throwing out angular blocks of lava which harden between eruptions, together with clouds of steam and dust which are extremely dense and black. Some of the ancients thought that it was beneath

Stromboli, "the lighthouse of the Mediterranean."

The Italian Government



this mountain, rather than Etna, that Vulcan was once supposed to have operated his forge.

Mt. Pelée. Mt. Pelée, overlooking the thriving city of Saint-Pierre, on the West Indian island of Martinique, had been dormant for fifty years. In April, 1902, steam was seen to rise from its summit, and during the following two weeks there were ejections of dust and cinders, accompanied by slight earthquakes. Sulfurous vapors filled the air, and torrents of mud poured down the slopes of the mountain.

Extremely viscous lava rose in the crater of Mt. Pelée, and hardened to form a solid plug sealing over the surface of the crater. Pent up forces within the volcano then began expelling material through lateral cracks in the walls, beneath the plug. On the eighth of May a tremendous explosion tore a gash in the south wall of the crater. Through this opening there issued a dark cloud consisting of extremely hot steam and other gases, filled with hot dust and other solid fragments up to many feet in diameter. This cloud raced down the side of the mountain at a speed estimated at more than a mile a minute, straight toward the town of Saint-Pierre. With the violence of a tornado it

Parícutin.

Photograph by D. B. Lawrence



Lava south and southwest of the cone of Parícutin. The sharp conical structure shown in the illustration was formed by the extrusion of rapidly hardening viscous lava from a secondary vent. Parícutin is situated on a plateau in southwestern Mexico, not far from the Pacific—a region which has seen much volcanic activity. It is unique in that it is the first volcano which scientists have been able to study from its inception; both scientists and nonscientists have been able to watch the birth of a volcano. A representative of the Smithsonian Institution describes the volcano's recent eruption as being "as spectacular as Vesuvius at its best."



Ezequiel Ordóñez

knocked down buildings, hurled statues weighing several tons about, uprooted trees. In a few seconds the ruins of the town were in flames, and all its 30,000 inhabitants, with four exceptions,¹ were dead. The cloud continued its course into the sea, where it destroyed all except one or two of the considerable number of ships lying offshore.

Following this catastrophe, the lava plug within Pelée's crater began slowly to rise. Parts of the rising column broke off, producing a shaft the shape of a spine. In seven months this spine had reached a height of nearly 1000 feet; it then began to disintegrate, and within a year or two had been reduced to a mere stub.

Mt. Pelée showed renewed activity from 1929 to 1932. Hot clouds were formed, which, however, were discharged to the north of Saint-Pierre. During this eruption many small spines grew out of the crater, but they soon crumbled.

¹Three of the four survivors died within a short time after their rescue. The only one to escape unscathed from Saint-Pierre was, ironically enough, a negro murderer under sentence of death, who owed his deliverance to incarceration in an underground dungeon with very poor ventilation.

Mt. Katmai. In 1912 there occurred in southern Alaska a volcanic explosion outranked in violence only by those of the East Indies, and certainly placing among the half-dozen greatest of historic times. Yet in this terrific eruption not a single person lost his life; it was several days, in fact, before the volcano involved was identified as Mt. Katmai.

Estimates place the amount of material blown into the air by this eruption at something like five cubic miles. Ten or twelve inches of white volcanic dust fell upon the island of Kodiak, one hundred miles away. Twenty miles from the volcano this white blanket hid the ground four feet deep, while the fall was still noticeable fifteen hundred miles or more away.

Large quantities of sulfurous gases were also emitted by Mt. Katmai during this eruption. Hundreds of miles from the eruption these vapors killed vegetation, corroded metal, or injured the skin of persons exposed to them. In Vancouver, B. C., and in the state of Washington 1500 miles away, brass was tarnished and linen fabrics disintegrated.

A few miles west of the volcano another type of eruption occurred at about the same time. Here the floor of a valley thirteen miles long and from two to five miles wide opened in several places and lava, blown almost instantly into solid particles of sandlike size, poured out upon the ground. This deluge of red-hot sand appears to have rolled like a viscous fluid through the valley, producing a very flat floor. Through openings in the ground issued thousands of columns of steam; for this reason the region was named the Valley of Ten Thousand Smokes.

Lassen Peak. Contemporaneous volcanic activity had been reported from several sections of the western United States during recent times, but it was not until Lassen Peak, in northern California, began erupting in May, 1914, that the existence of an active volcano within the borders of this country was definitely recognized. Lassen Peak is located at the southernmost end of the Cascade Range. It was formed by the extrusion of a large mass of very viscous lava, of which the outer portions have crumbled away in response to internal pressures of expanding lavas, forming extensive talus slopes. In 1914 gases were given off, and some fragmental materials were thrown out. In the following year explosions occurred, two of them of extreme violence. The force of these explosions was insufficient to dislodge the volcano's



Canadian National Railways

At Bulkley Gate, British Columbia, Bulkley River works its way through a narrows produced by an eight-foot dike.

plug, but was expended, as in the case of Mt. Pelée, laterally, from beneath the plug. Rocks were hurled to a distance of ten miles. During 1916 Lassen's explosiveness subsided.

There was another small eruption in 1925. Activity has since died down, and is at present confined mostly to the emission of gases.

Parícutin. Without doubt, one of the most magnificent spectacles of the present day is the continuing eruption of Mexico's new volcano, Parícutin, illustrated on pages 316 and 317. The existence of this volcano dates from February, 1943, when a column of steam and dust burst from the ground in the midst of a cornfield in a highly volcanic plateau region about 200 miles west of Mexico City. There followed a most spectacular eruption. Within a week a cone 500 feet high had been built up. Within two years this cone had reached a height of 1500 feet. During the eruption lava destroyed two villages, while the countryside for a distance of thirty-five miles was desolated by a blanket of ash.

Summary of volcanic types. The volcanoes which have been described show a wide diversity of eruptive characteristics, some of them so distinctive that they serve as a basis for classifying all such phenomena. The following classifications have been set up, to which volcanic eruptions are sometimes referred:

1. The *Hawaiian type*, characterized by the relatively quiet extrusion of very fluid lava, through which gases find egress with little difficulty.

2. The *Strombolian type*, in which the lava is more viscous than in the Hawaiian type, the escape of gas being attended by explosions of mild to moderate character. Incandescent lava and clouds are ejected almost continuously in a typical case.

3. The *Vulcanian type*, in which the lava is still more viscous, solidifying on the surface between eruptions, resulting in the occasional blowing off of the crust. Clouds forming above a volcano of this kind are not luminous, but are dark and typically of a "cauliflower" shape.

4. The *Vesuvian type*. Explosions of this class of volcano are still more violent than those of the Vulcanian type. Lavas usually break through lateral fissures, preceding the explosive expulsion of gas-filled lavas from greater depths, which solidify into ash and cinders. The "cauliflower" clouds are of great size, and rise to a great height.

5. The *Pelean type*, in which the lava is extremely viscous and forms in the vent a solid plug or dome which cannot be dislodged. Explosions therefore expend themselves through the walls of the volcano, producing dark clouds consisting of gases, dust, and larger solid particles.

United States Forest Service



Columnar jointing, Devil's Post Pile, San Joaquin River, California. Since this type of columnar structure always forms at right angles to the cooling surface, it is evident that this mass is part of a horizontal lava flow or sill. The Devil's Tower of eastern Wyoming (see page 325) shows the impressive scenic possibilities of columnar jointing, as does Fingal's Cave in Scotland and the Giant's Causeway in Ireland.

INTRUSIVE STRUCTURES

Characteristics of intrusions. Because of its slow rate of cooling an intrusive mass will be almost entirely crystalline, and the crystals, with the probable exception of those near the edges, will be large. Further, the pressure under which the intrusion solidifies holds the contained gases to a small volume, the evidence of their presence appearing in the solidified rock only as microscopic pores; no scoria, pumice, or vesicular structure of any sort can develop.

Another feature often observed in intrusive rock is a type of jointing described as *columnar structure*, illustrated on pages 320 and 325. All deeply buried magmas develop joints as a result of the contraction which accompanies cooling. Columnar jointing is most common in basaltic magmas of flat or tabular form. Contraction appears to proceed around certain equally spaced centers, causing the rock to break up into strikingly spectacular columns, usually hexagonal, and often of extremely regular size and shape. The jointing is at right angles to the cooling surface; that is, the elongated prisms of rock will be horizontal in a vertical magma-filled fissure and stand upright in a sheet which spreads out horizontally.

The Giant's Causeway in Ireland and the Devil's Post Pile near the head of the San Joaquin River, California, are two of the best-known examples of columnar jointing. Mateo Tepee, in Wyoming, near the edge of the Black Hills, also shows this structure, the joints being vertical near its summit and approaching a horizontal attitude lower down; these positions, indicating cooling surfaces both on top and at the sides, have been invoked as evidence that Mateo Tepee is a volcanic neck rather than the remains of a once larger mass.

The intrusive nature of an igneous mass can be established with certainty if the rocks above, as well as those below, show the effects of heat or other alteration due to the proximity of the magma. Metamorphism of only the underlying rocks would indicate the mass to be extrusive; changes affecting the overlying rocks show these to have been formed before invasion by the igneous mass, which is thereby shown to be intrusive.

Dikes. *Dikes* are flat, tabular masses of intrusive rock which have solidified in fissures in the earth. They usually stand at steep angles, like that illustrated by the photograph on page 319, and in many cases

connect larger intrusive masses above them with the source of the magma below. In size they range from the fillings of tiny crevices to extensive formations hundreds or even thousands of feet thick and many miles in length; a dike in South Africa has a length of 300 miles and a width of from 3 to 4 miles.

Dikes may occur singly or in large groups. They are often found in connection with volcanoes or large intrusions; in many such cases they radiate outward from the larger body. They may also show a parallel arrangement, reflecting the presence of parallel cracks in the rocks.

Some dikes offer less resistance to erosion and weathering than do the rocks enclosing them. Upon long-continued exposure, the removal of the material of the dikes leaves long valleys with straight, parallel sides. If, as is more commonly the case, the rocks constituting the dikes are of superior resistance, they eventually come to stand out as prominent ridges. Among the best examples of dikes are the large number radiating away from the Spanish Peaks in Colorado. Some dikes, including those just mentioned, exhibit columnar structure. Among other conspicuous dikes might be mentioned those extending away from Shiprock, the remnant of an ancient volcano of north-western New Mexico.

Sills. *Sills*, or *sheets*, are flattened intrusive bodies which lie essentially parallel to the stratification of the enclosing rocks; they are often

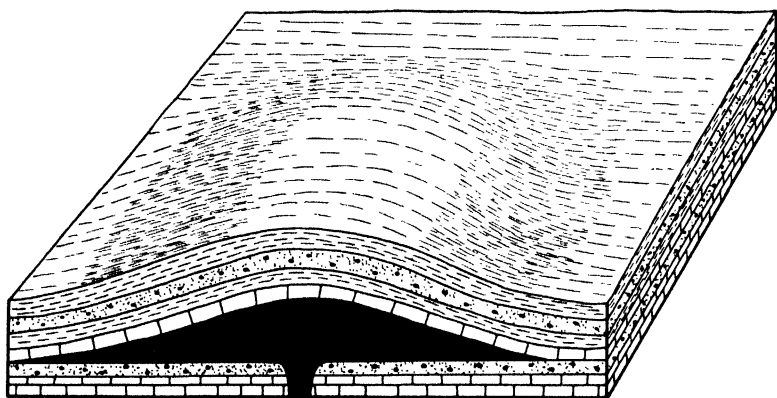


Diagram of laccolith, an intrusion based on a bedding plane which has raised the overlying strata.

nearly horizontal, but may be inclined. The path of intrusion of sills is along bedding planes, although they may cut across strata to some degree. During the intrusion the overlying rocks are lifted bodily.

Like dikes, sills vary widely in size; some of them cover thousands of square miles. As in dikes, also, columnar jointing frequently develops, as in the 800-foot sill which forms the Palisades along the west side of the Hudson River and the two sills standing out prominently in the walls of Yellowstone Canyon; the latter may be seen in the illustration on page 324. Since the columns produced by this type of jointing are always at right angles to the cooling surface, those constituting the Palisades stand vertically.

Laccoliths. Sometimes molten rock working its way between strata is so viscous that instead of extending itself in the form of a sill it thickens locally, arching up the layers above it, forming a massive intrusion known as a *laccolith* (Greek, "stone cistern"). A laccolith may be irregular in shape, or it may be oval, lenticular, or hemispherical, but typically it has a flat base, resting upon sedimentary rocks; this essential condition, as well as the general typical shape and relation to underlying and overlying rocks, is shown in the diagram on page 322. Its lateral edges may be clearly defined, or they may thin out until indistinguishable from sills.

For some reason laccoliths are especially well developed in the area east of the Rocky Mountains. They were first recognized as a distinctive type by G. K. Gilbert in the Henry Mountains of Utah, the largest of which has a diameter of about four miles. Several very much larger laccoliths have since been found; one, northwest of Lake Superior, has a volume vastly greater than all of the Henry Mountains group. Bear Butte in the Black Hills region of South Dakota and the Moccasin Mountains of Montana are laccoliths; others are known in Colorado, Arizona, and elsewhere. The Devil's Tower (p. 325) may be a laccolith, although its origin and nature are still somewhat obscure.

In a few cases the floor of a laccolith has sagged, causing the collapse of the overlying rocks as well. The resulting basin-shaped structure is known as a *lopolith*.

Necks. Volcanic necks, which have already been described as the hardened plugs which fill the throats of volcanoes, may be from a



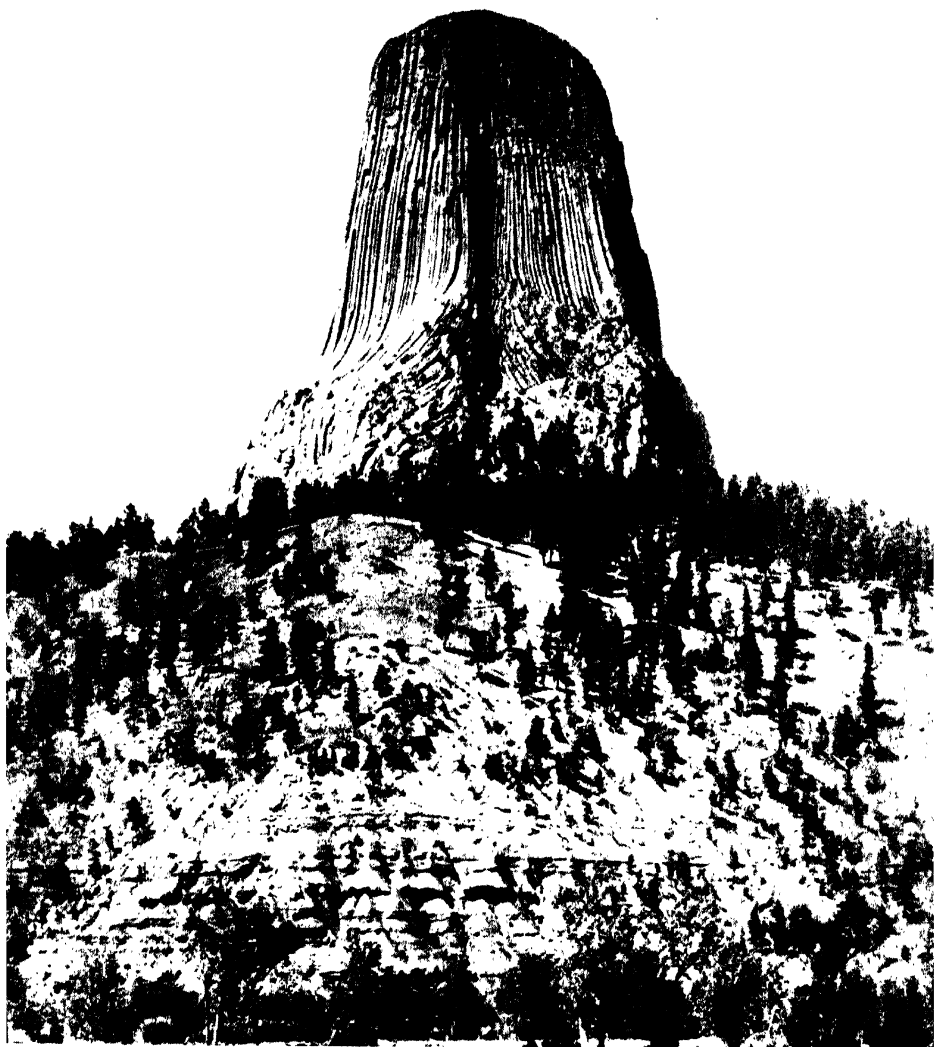
United States Forest Service, photograph by A. A. Munner

Part of the great Idaho batholith. Sawtooth Mountains, central Idaho.

Two basaltic sills outcrop prominently in the walls of the Canyon of the Yellowstone, Yellowstone National Park, Wyoming. Both exhibit columnar jointing.

National Park Service, photograph by George A. Grant





United States Geological Survey, photograph by N. H. Darton

Devil's Tower, eastern Wyoming. Considered by some to be a volcanic neck, by others a laccolith. Note columnar structure.

few hundred feet up to several thousand feet in diameter. Nearly all the diamonds now being mined are found in ancient volcanic necks in South Africa.

Batholiths and stocks. An intrusive mass of great size with no known floor is called a *batholith*. Batholiths, from which the magmas feeding lesser bodies such as dikes, sills, and laccoliths often stem,

generally broaden downward as far as they can be traced. The rock of which they consist is almost always granite, granite gneiss, or rock of similar composition.

Batholiths are sometimes of compact or irregular shape, but are usually elongated, forming the cores of great mountain ranges. Among the largest in America is the Sierra batholith, exposed by the dissection of the Sierra Nevada Mountains. This intrusive mass is 400 miles long. Extending from the Canadian border and forming the heart of the Coast Range Mountains is a still larger batholith, 1200 miles in length, and in places 100 miles or more in width. The largest batholith in the United States is in central Idaho; its exposed surface, part of which is illustrated on page 324, covers an area of 16,000 square miles.

A *stock* is a smaller intrusion having an irregular or an unknown base. It differs from a batholith in size, and from a laccolith in that it cuts across the strata it invades, and is not known to have a floor. The distinction between batholiths and stocks is sometimes based upon an arbitrary size limit, masses exceeding forty square miles in area being classified as batholiths, those of smaller size as stocks.

SECONDARY VOLCANIC PHENOMENA

In addition to the major expressions of vulcanism—volcanoes and intrusive masses—a number of lesser forms are produced by volcanic heat. These include geysers, hot springs, and a number of kinds of gas vents. These structures are closely associated, and often grade into one another.

Geysers. A geyser may be defined as an intermittently eruptive hot spring. Geysers are rare, and are found only in regions of present or past volcanic activity. They are notable at the present time only in Iceland, Yellowstone Park, and New Zealand, although known to occur also in Mexico, the Azores, South America, Japan, Malay Peninsula, Tibet, and a few other places. Of the geysers of the principal regions, those of Iceland have decreased considerably in activity since their discovery, and those of New Zealand have suffered such changes that their future is uncertain.

The best display of these queer springs is to be seen in Yellowstone Park, where about two hundred of them are associated with three thou-



Waiḡite Geyser, Whakarewarewa, New Zealand, showing deposits.

sand or more hot springs and steam vents. The Yellowstone geysers are for the most part grouped into three valleys or basins in the west section of the Park. Here are geysers of all descriptions: tiny "minute men" which erupt diminutive fountains every few minutes; geysers so great that they emit enough water to supply a fair-sized city; geysers which erupt on a regular schedule, others which are most unpredictable; some the eruptions of which are over in a few seconds, others which continue in activity for hours. Eruptions vary in height from an inch or so to hundreds of feet. Some geysers erupt into pools of water. Others build mounds of geyserite around their openings.

When subterranean conditions are fairly stable the activity of a geyser follows a regular pattern, as in the case of Old Faithful. For a long time this well-known geyser erupted with but little variation at intervals of about one hour, although in recent years it has shown an inclination toward irregularity. Its output of water amounts to about 10,000 gallons at each eruption, the stream being thrown to a height of well over 100 feet. Giant Geyser erupts at intervals of from one to two weeks; its activity continues for nearly an hour at a time, its water column reaching a height of 250 feet. Some geysers erupt at intervals of months, or even years.

A geyser eruption usually begins with rumblings or gurglings. These are followed by a quiet expulsion of hot water, or by the ejection of water semiexplosively in a series of spasmodic outpourings. This may continue for several minutes. At the height of the eruption water is hurled out violently, in some cases to a great height, perhaps approaching 1000 feet, as in the case of a geyser of New Zealand; such a height, of course, is very exceptional, most eruptions lifting water less than 100 feet.

The exact causes of geyser action are not known with certainty, but it is agreed that eruptions are the result of the sudden conversion of superheated water into steam when the pressure upon the water in the lower parts of the geyser is lessened by the preliminary outflowing at the surface. The heat responsible for the action comes from heated rocks at some depth below the surface, and is transmitted to the water in the geyser largely by steam and other hot vapors. Most of the water present is ground water which has seeped into the underground cavities of the geyser, although some of it comes from the condensation of the steam arising in the nearby magmas.



National Park Service, photograph by George A. Grant

Relief of pressure on superheated water causes this eruption of Old Faithful geyser in Yellowstone Park.

Terraces deposited by Mammoth Hot Springs, Yellowstone Park. Hot waters ascending through thick limestone beds have deposited calcium carbonate, which is delicately colored by microscopic plant life.

Union Pacific Railroad Photograph





Geyserite forming around the mouth of Eagle's Nest Geyser, North Island, New Zealand. Geyserite is a silicious deposit often laid down as the result of evaporation or change in the chemical nature of the silica-bearing waters. It often takes forms of great beauty, appearing as hard incrustations, filaments, or flower-like structures. A splendid display of geyserite can be found in the Upper Geyser Basin of Yellowstone National Park, although it occurs in all the major geyser regions of the world.

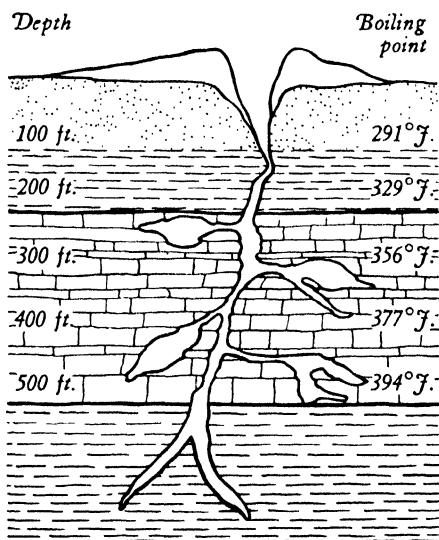
The geyser tube or pipe is an opening extending downward into the ground for an unknown distance. It is considered to be crooked or constricted in some way, or to ramify among the rocks, enlarging in places to form cavities in which steam can be trapped; at any rate, there is no free circulation of water within it. These conditions are shown diagrammatically on page 331. If the tube were straight or of large diameter, or without cavities at levels such as to prevent free communication with the surface, heated water at the bottom would rise to the top, thus creating a circulation which would warm all the water in the tube to the same temperature; under these circumstances there could be no genuine geyser action. But whatever irregularities exist in the tube prevent the water from circulating and provide the condition upon which geyser action depends, namely, that water in some way be held in the lower levels until it has become heated above the temperature at which it ordinarily boils.

Under standard atmospheric pressure—14.7 pounds per square inch—water boils at 100° C. As the pressure increases, the boiling point rises. For example, in a vertical column of water the pressure at a depth of thirty-three feet is about double that exerted by the atmosphere on the surface, and at this depth boiling will not occur at 100°, but at about 120°. Under 100 feet of water, a temperature of 144° C. (291° F.) will be required to cause boiling.

Let us assume that the water at the bottom of a geyser tube has been heated to near the normal boiling point. This hot water rises from the bottom through cooler water, until its upward progress is stopped by some sort of constriction in the tube. Soon all the water below this constriction has reached a temperature of 100° , at which point it would boil but for the pressure exerted by the weight of the water above it. Its temperature continues to increase, until at length a point is reached at which a little of the water, in spite of the pressure, changes into steam. This vaporization may occur below the constriction in the tube, or it may occur nearer the surface where the water is cooler but under less pressure. When water becomes steam it expands to more than 1000 times its original volume; thus the vaporization of even a small part of that in the tube forces some water toward the surface. A little spills over the rim; this relieves the pressure upon that below, allowing the formation of more steam. Water is poured out the top in rapidly increasing volume, culminating in an eruption of almost explosive violence.

Workable models illustrating this explanation of geyser action have been made, and there is no reasonable doubt that the principles given are the basis of geyser eruptions. However, there are cases involving additional factors. Some geysers, for example, eject a great deal more water than could be accommodated by the known volumes of their tubes; in these instances the tubes must be of a complex character,

Diagrammatic representation of a geyser tube, showing the conditions believed to be responsible for geyser action. Note the constricted portions of the tube, which presumably interfere with the formation of convection currents and permit the accumulation of water in the lower parts of the tube until heated far above the normal boiling point. The boiling points indicated for the different depths assume that the tube would be completely filled with water, which would only be true towards the end of each period.



communicating with larger cavities. Steam reaching these cavities from the magma at first condenses, liberating large amounts of heat. When the temperature of the water present in the cavities has been raised to the boiling point under the existing pressure, further additions of steam do not condense but remain in the form of vapor, and help to develop the pressure necessary to force water out of the mouth of the geyser.

Continued repetition of these processes eventually cools the magmas furnishing the energy for the activity. The geysers of Yellowstone Park have shown little evidence of dying down. Some have become extinct, others have newly come into existence; but the cause of these changes is probably superficial alterations in the underground systems of steam and water circulation.

Hot springs and fumaroles. Although some thermal springs occur in nonvolcanic areas, deriving their heat from great depths, the majority, and especially those of which the waters are exceptionally hot, are to be found in regions of present or recent volcanic activity, in which we may assume that intrusive masses of high temperatures lie close to the surface. The water of these springs, like that of geysers, is partly of meteoric origin, and in part the product of condensation of steam emanating from the intrusive magmas. Geysers may become ordinary hot springs when their activity dies down.

The Mammoth Hot Springs of Yellowstone Park are notable for their remarkable deposits of travertine, which has been laid down in the form of a series of terraces. While wet, the deposits are delicately colored by microscopic organisms, but they fade to an alabaster shade upon drying out.

A *fumarole* is an opening in the ground from which steam or other gases escape. Hot springs may dry up and become fumaroles during dry seasons, resuming their role as springs upon the return of more humid weather conditions. The water of the spring is presumably heated by the condensation of steam rising from near-by magmas; if too little water is present to cause condensation, the steam itself emerges at the surface opening, which thus becomes a fumarole.

In addition to steam, numerous other gases are exhaled by some fumaroles. Among these are carbon dioxide, hydrogen sulfide, sulfur dioxide, hydrogen chloride, and methane. Chlorides and fluorides of



National Park Service, photograph by George A. Grant

Fumarole in Lassen Volcanic National Park.

iron, lead, and other metals may be volatilized and carried upward toward the surface and deposited. When hydrogen sulfide is brought in contact with the air it is often oxidized, yielding free sulfur, which is dropped around the mouth of the vent, sometimes in sufficient quantities to justify exploitation.

A fumarole which gives off sulfurous vapors in some quantity is termed a *solfatara*. La Solfatara, a volcano west of Naples, is a typical example of this sort of fumarole. Its last eruption was in 1198, since which time its activity has been limited to the emission of gases. Sulfur is recovered from this locality, as well as from solfataras in Japan, Mexico, and elsewhere.

Carbon dioxide also is prominent among the gases of fumaroles. Death Gulch, in Yellowstone Park, is a valley in which this gas accumulates to a sufficient depth to suffocate small animals that wander into it. A number of other similar valleys are known.

Fumaroles are well developed in Yellowstone Park and in the vicinity of Lassen Peak; but these phenomena reach their climax in the Valley of Ten Thousand Smokes, in southern Alaska. Here steam



Boiling mud or paint pot, Whakarewarewa, New Zealand. These phenomena, resulting from the escape of steam through pools of mud, may be either gray or brightly colored. If the mud is thrown up into the air by the percolating steam, a "mud volcano" results, which may build up a diminutive crater around its opening.

issues from the ground in thousands of jets, some of almost microscopic dimensions, some hundreds of feet high, some coming from definite vents, others working their way out of the ground en masse between the grains of rock. The temperatures of some of these steam jets is very high, in some cases reaching 650° C.

Allied to hot springs and fumaroles are a number of phenomena known as boiling springs, paint pots, and mud volcanoes. Boiling springs are pools through which bubbles of steam rise to the surface. If the supply of water is adequate, these springs overflow, carrying away mud particles and leaving the water clear. Others, without outlets, are masses of agitated mud, and are appropriately called paint pots, one of which may be studied in the illustration above. Mud volcanoes are vents from which viscous mud is intermittently cast into the air by the pressure of escaping gases. The mud sometimes forms conspicuous cones surrounding the "crater." Mud volcanoes may result from the pressure of steam, although some are caused by the release of natural gas associated with petroleum deposits.

VOLCANOES AND MAN

Volcanic disasters have reaped a toll of human life and property surpassed by but few natural agencies. On the other hand, eruptions have in some cases yielded beneficial effects. Among these is to be listed soil of great fertility, as is evidenced by the persistence with

which the slopes of Etna, Vesuvius, and other volcanoes have been occupied and cultivated, in spite of the ominous presence of the slumbering mountain. Some volcanoes and solfataras have been exploited as sources of sulfur, and recently other chemicals, such as boric acid and carbon dioxide, have been recovered from these sources. Steam for use as a source of power has been obtained from fumarole fields in Italy and California, and the possibilities of similar fields in Java are being investigated.

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XIV · DEVELOPMENT OF LANDSCAPES



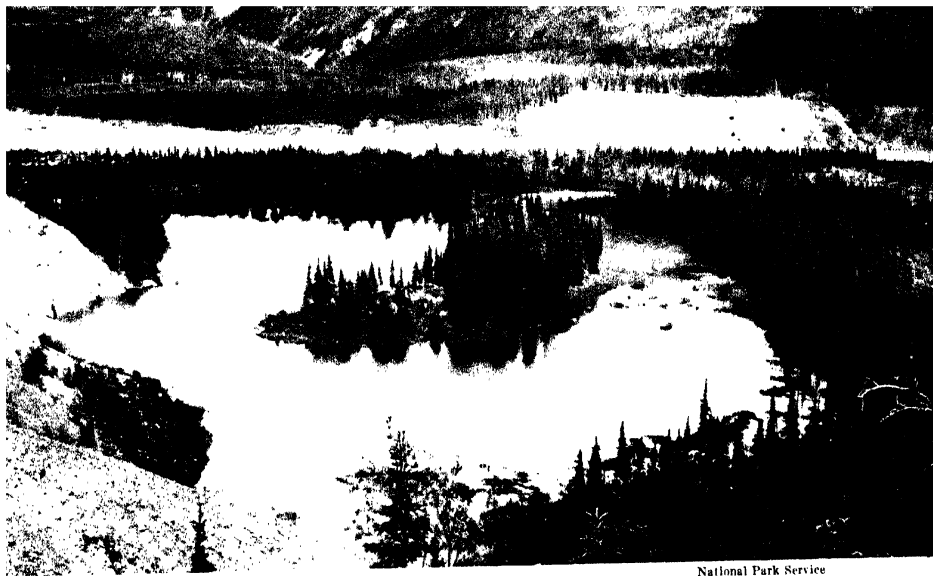
As we look upon the various topographic forms exhibited by the earth's surface, the infinite array which unfolds itself appears at first to defy systematic classification. It is only when a study is made of the erosive, transportational, and depositional effects of the several geological agents upon structures of differing character that a semblance of order begins to appear among the magnificent irregularities that give the present face of the earth so much of beauty and interest.

These irregularities are, in a literal sense, almost infinite in their variety. No two of them are just alike, none have had identical histories. In all cases, they must be studied from at least three points of view. Their present topographic outlines will depend in large part upon their *structure*—the original attitudes of the rocks of which they are built, and the relationships of component parts of differing natures. They will depend, further, upon the *processes* which have been acting upon them, and these processes in turn will be determined by such factors as climate, elevation, and the nature of the rock involved. Finally, the aspect of any landscape will be influenced by the *stage* of its development, the degree to which the agents of erosion have performed their work. An adequate comprehension of the stages of

Soil Conservation Service



At the beginning of the geomorphic cycle, rain water runs off aimlessly, following the slope of the surface, forming disconnected gullies. The development of the gullies shown here was obviously promoted by poor agricultural practice. The farmer planted his crops running down the incline, instead of across it. A single rain may remove as much as two inches of topsoil, sometimes even more, from a field like the one shown here.



National Park Service

Upland lakes, always of comparatively brief duration, are indicative of topographic youth. Horseshoe Lake, Alaska.

Gullies begin to unite, gradually forming a more or less integrated pattern.

Soil Conservation Service, photograph by R. F. Copple



development through which a region of certain structure has passed in response to the activity of the geological agents operative in the region in question makes it possible to trace the history of a topographic area backward to its initial state, and thus helps, not only toward a more intelligent understanding of natural scenery, but in the unraveling of some of the earth's ancient puzzles.

Because so large a number of factors, which are themselves infinitely variable, enter into the sculpturing of every region, producing countless topographic forms, the evolution of an area cannot be reduced to an exact formula. It is possible only to sketch its development along broad lines for the principal types of regions under several general types of climate.

The changes which a region passes through as a result of the action of the agents of erosion constitute its *cycle of erosion*, or *geomorphic cycle*. As a convenience in describing the degree of erosion which a region has suffered, the terms *youth*, *maturity*, and *old age* are commonly employed. As with the erosional age of a stream, these terms do not imply the passage of definite periods of time, but the attainment of certain fairly definite conditions of erosion. A region in old age may even be eroded back into a condition of topographic maturity, through a renewal of the power of the agents acting upon it. Youth, maturity, and old age, then, are to be regarded as *stages* of development, rather than as *ages*.

Because of similar terminology, confusion sometimes arises in connection with the relationship of the age of a region and that of the streams traversing it. While the degree to which erosion has progressed is the determining factor in each case, the two must be appraised independently; the age of a stream may not correspond to that of the region it drains.

In general, the stage of youth of any sort of region—plain, plateau, mountain, seacoast, or interior basin—is characterized by the persistence of most of the original surface of the structure. That is, erosion has as yet had but little effect upon it, except locally. Maturity is marked by notable relief, with little of the original surface remaining intact; this is a time of variegated topography, of prominent details, and often of fine scenery, although these features are also frequently present in youth. Contrast the topography represented on the Soda Canyon, Colorado, map (p. 447) with that shown on the Edmond,



Soil Conservation Service, photograph by Chapman

*The stage of youth begins with the establishment of definite drainage patterns.
Note that most of the original surface remains untouched by erosion.*

*Eventually little of the original surface remains; the countryside is
reduced to slopes.*

United States Forest Service, photograph by P. S. Bieler



Oklahoma, map (p. 440); in the first case, most of the land surface has hardly been touched by erosion, while in the second we see typical mature topography. Old age is the period when most of the irregularities of the landscape have been erased; the surface typically appears as broad expanses approaching a flat condition, with only occasional isolated masses of especially resistant or protected material remaining above the general plain.

In the following pages a generalized picture will be given of the development through these stages of regions under a number of common and widespread conditions.

THE EROSION CYCLE IN A TEMPERATE HUMID REGION

Several agents, of course, commonly co-operate in the sculpture of a landscape. In temperate regions of even moderate rainfall the forces chiefly responsible for modification of the land surface are running water and chemical weathering.

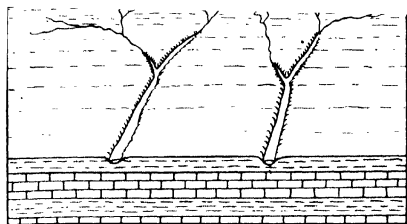
Let us assume that the region under consideration is nearly level and stands at a considerable elevation above the sea. At first rain water runs off rather aimlessly, following depressions in the ground, soon developing a number of disconnected gullies. These consequent streams gradually unite, forming a more or less integrated pattern. When they have cut through the weathered mantle to the bedrock, they adjust themselves to the character and position of the underlying rock, changing their courses accordingly. The photographs on pages 336, 337, and 339 should be carefully studied at this point, as they show the successive stages in the development of a drainage pattern.

In the young region there are but few streams, and these are poorly branched. Most of the area of such a region remains untouched by river valleys. Under these conditions of poor drainage, water is likely

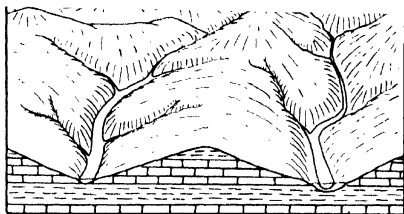
United States Geological Survey, photograph by Fuller



Because of general extensive uplifts in geologically recent times, good examples of topographic old age are rare. Such an example, however, on a restricted scale, is the valley of the Wabash River, Indiana, shown at the left.

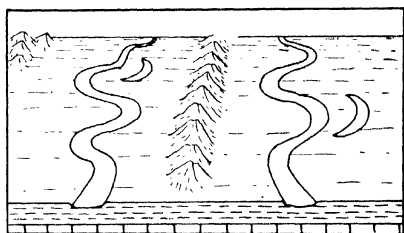


a



b

The cycle of erosion in a temperate humid region. (a) The stage of youth, marked by the presence of a few shallow stream valleys with poorly developed tributaries. (b) The same region in maturity, at which point the surface has been entirely dissected. (c) Old age in the region, which is now peneplained (p. 342).



c

to accumulate in low places, forming lakes and swamps. These conditions are usually conspicuously evident in recently glaciated areas, as can be seen on the Whitewater, Wisconsin, map on page 450, and in the photograph on page 202. Lakes and swamps, however, as we have seen, do not endure. Inflowing streams fill them with sediment, outflowing streams cut down their outlets, vegetation grows upon and within them, adding its organic material to the sediment filling their basins. At length all lakes will have disappeared. Waterfalls, rapids, and potholes will have been ground away from the river beds. Tributaries will have jutted out from the main streams, and will themselves have branched and rebranched.

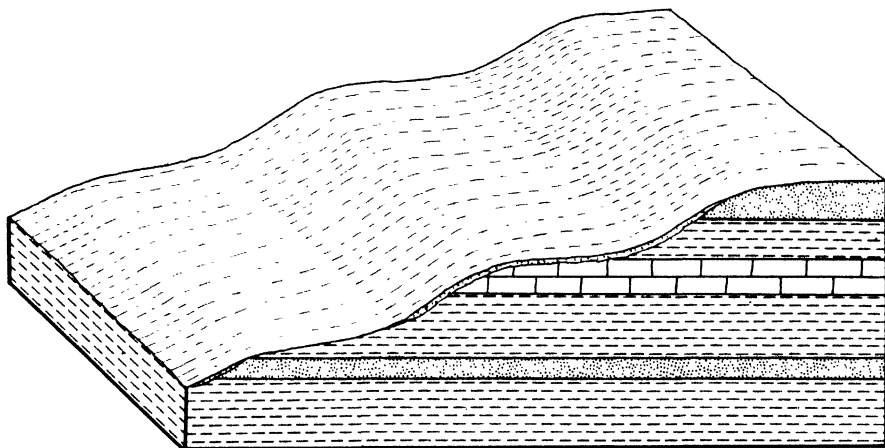
The course taken by erosion at this point depends upon the attitude of the rocks of the region. If these rocks are horizontal, the branching tributaries cut the intervening lands into ridges, which subtributaries dissect into individual hills. If on the other hand the rocks are tilted, streams concentrate on the weaker layers, producing hogbacks or cuestas. Ordinarily, however, none of these elevations attain notable development, for every tendency of a humid region to develop any angularity of outline is held in check by the weathering process. (Compare diagrams, pp. 342 and 346.) Chemical weathering carries its destructive work to such a depth that the rock near the surface is usually

too soft or weak to stand for long at high angles. Valley walls crumble and wash or slide downward into the streams. Tributaries eat greedily into the weathered divides, furrowing and wasting them. At length all steep slopes and sharp angles have melted away, and the surface has become an expanse of mellow curves.

This is the stage of maturity, a time of extensive dissection and maximum relief. Theoretically, all the land is now reduced to slopes¹; every drop of rain that falls finds a sloping surface to urge it onward into a stream valley. The strong relief promotes soil creep. A comparison of the illustrations on page 339 will emphasize the differences between the stages of youth and maturity. Note that in the former little erosion has been effected outside the valley, while in the latter the original surface of the land has been almost destroyed.

This is also a time of maximum change. The lands are worn lower and lower, and old age comes on. Ultimately, the region is reduced to low, rolling plains, which become ever more and more nearly flat; a district in this stage is shown on page 340. A surface of this kind is called a *peneplain*, which can be defined as a land surface made almost flat by erosion and weathering.

Old age is the stage during which a region slowly progresses through these final steps toward the condition known as *base level*,



Pronounced cliffs cannot long endure in a humid region. Compare illustration on page 346.

¹Realization of this theoretical condition depends upon the elevation of the region, the amount of rainfall it receives, and other factors.

which is the lowest level to which a region can be reduced through the action of external agencies. In a district of humid climate it approximates sea level, although an entire drainage basin can never be reduced quite to the level of the sea by the action of streams alone.

A study of the photographs referred to above should be made in connection with the diagram on page 341, which shows the development of a region from youth to old age.

THE CYCLE IN A DRY CLIMATE

In a temperate region of arid or semiarid climate, an elevated and essentially flat surface will undergo a metamorphosis similar to that of the humid district, although with certain modifications. In the drier section, stream flow will generally be much more irregular, not only because of greater irregularity of rainfall, but because vegetation is usually too scanty to exert an important retarding effect upon runoff. Hence most streams will be intermittent; their eroding power, in many cases, will be considerable, because of the rapidity of the runoff and because the ground is largely unprotected by vegetation.

Weathering in a dry region is of the slow, mechanical type. Since this form of weathering has little effect on rock below the surface of the ground, stream banks stand steeply, while the channels are deepened at a relatively rapid rate. Valleys become canyons, if elevation is great enough; even small gullies and ravines take on canyon shapes. Maximum downcutting and minimum weathering may even result in square-cut or box-shaped canyons.

Depressions or basins are likely to exist in the arid as in the humid region. In the earlier stages of development, the water of the intermittent streams evaporates or sinks into the ground before it can reach the bottoms of the basins. But with the growth and development of the stream systems, water is at length carried into the lowest parts of the depressions, forming playa lakes. In this way the floors of the basins are gradually raised, although when dry some of the sediment on the surfaces of the playas is removed by deflation. Death Valley (p. 344) offers an instructive example of a basin subjected to these conditions.

When basin-filling has continued for some time, streams from the higher basins will have become so elevated that they may find an

outlet, flowing out and into basins at lower levels. This integration of the drainage system may be taken to mark the stage of maturity. Base levels for the streams traversing the higher basins have now been lowered; increased gradients cause rapid and complete dissection of the remains of the playas of these basins.

The aspect of mature topography in an arid section is markedly different from that of one provided with abundant rainfall. In a dry country there is in most places little weathered material to obscure the structure of the bedrock, and to soften the outlines of the topography. Buttes, monuments, and mesas stand out sharply as exemplified in the photograph of part of Monument Valley shown on page 345. Horizontal strata are carved into terraces, the harder layers forming

Death Valley, California, an arid basin without exterior drainage. The products of erosion are piled in great alluvial fans around the base of the rim. Death Valley also presents an interesting study in badland topography. The rocks shown here are relatively young and are poorly consolidated, and are eroded rapidly by swiftly flowing streams.

Bureau of Reclamation



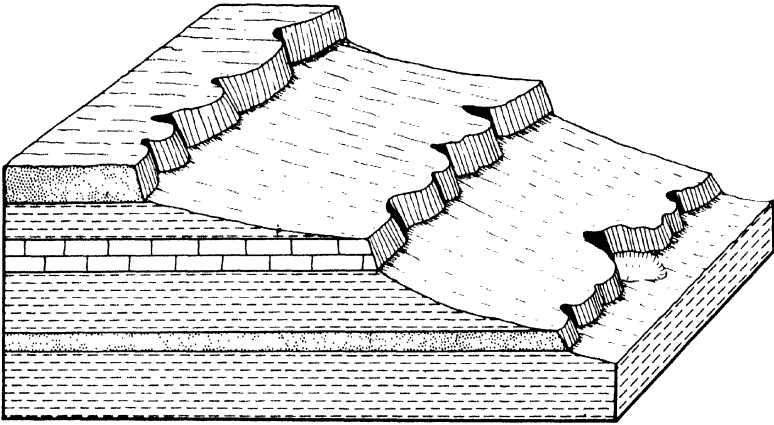


Utah Department of Publicity

Monuments and buttes, the remnants of a once vast plateau, dot the surface of Monument Valley, in northern Arizona and southern Utah, producing an atmosphere of serene grandeur.

cliffs, the softer, slopes. Tilted strata similarly exhibit angles which would be covered by characterless mantle rock in a more humid climate.

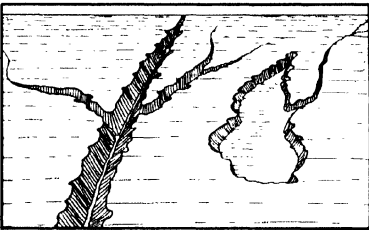
Soft rocks at considerable altitude above the main streams of the region may be converted by sheet, gully, and rain erosion into an intensely dissected landscape known as *badlands*. Badland topography, of which the illustrations on pages 88, 344, and 347 serve as examples, presents a weird and bewildering aspect of countless ravines, barren slopes, jagged or knife-edged divides, and rounded, conical, flat-topped or spire-shaped hills. Vegetation is absent or nearly so, as occasional



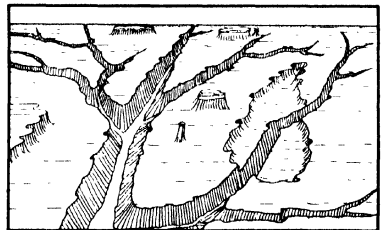
In an arid region the wearing away of horizontal layers of rock of differing hardness is likely to result in cliffs and terraces. Compare illustration on page 342.

heavy showers wash away weathered material before plant life can gain a foothold.

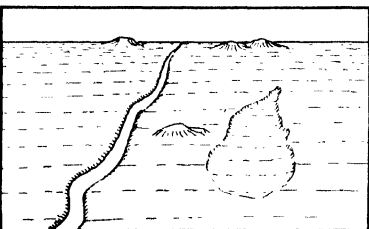
Although badland topography is to be found in almost every western state, the finest example of it is to be seen in southwestern South Dakota and northern Nebraska. Here the White River has sunk to a considerable depth below the surrounding country. The climate is not humid enough to promote rapid weathering, and such weathered



a



b



c

The erosion cycle in an arid region. The stages are the same as those indicated in the illustration on page 341. Note the progressive integration of drainage systems as basins are filled.



Canadian National Railways

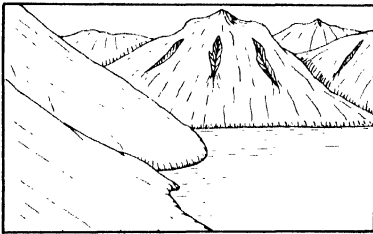
Badlands. Red Deer River district, Alberta.

materials as do form are washed away before plants can take root in them. Consequently the soft rocks have been gullied to an unparalleled degree. Bryce Canyon, Utah, is another striking example of this type of erosion. Here a valley only a few square miles in area but 1000 feet deep is literally filled with a fantastic array of towering pinnacles of the most extravagant colors.

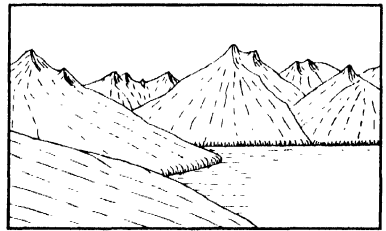
Ultimately the arid region, like the humid, is reduced to a peneplain. As the lands are reduced, rainfall generally decreases. Wind becomes relatively more important as an erosive agent. In very arid regions, wind may reduce the land surface to below sea level. Base level, in such a region, is reached only when the rock becomes too damp to be removed by deflation. These stages are shown in the diagram on page 346.

THE CYCLE IN MOUNTAINOUS REGIONS

The stages in the cycle of erosion can be distinguished in a mountainous country by the same general definitions which apply to the more nearly level regions. Mountains are to be considered young as long as their shapes are determined chiefly by their fundamental structures, rather than by the effects of erosion. Streams coursing down their sides cut local canyons, but leave the bulk of the masses un-

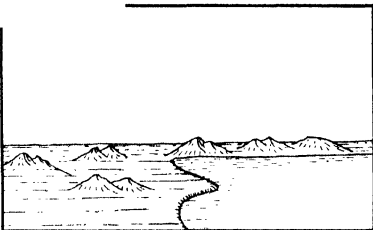


a



b

c



The erosion cycle in a mountain region. Stages are the same as in the illustration on page 341.



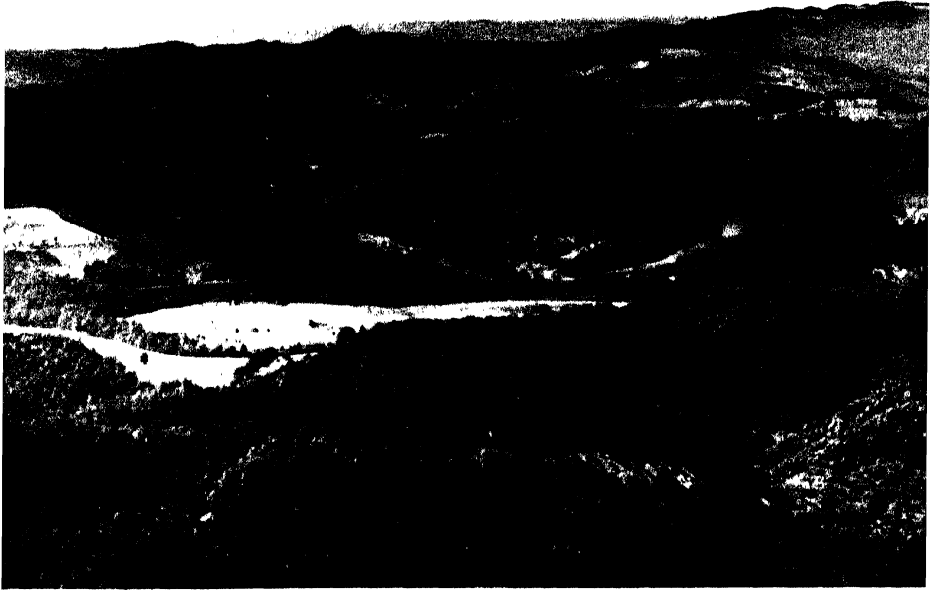
Pikes Peak Information Bureau

Youth in a mountainous region. Pikes Peak and its surrounding mountains show the effects of occasional cirques and canyons, yet have escaped extensive dissection.



Northern Pacific Railway

The savage peaks of the Grand Tetons speak of severe erosion by glacial action. Several opposing cirques, surrounding the flanks of a lofty peak, carve out these typically pyramidal shapes.



Norfolk and Western Railway

Old mountains, weathering under humid conditions, are at last reduced to a condition of rounded curves and gentle slopes.

touched. If glaciers are present, occasional cirque-excavated cavities will appear in their summits and sides; but the original appearance of the mountains will not have been greatly altered. The southern Rockies (p. 349) and the Bighorns are examples of mountains in this stage of erosion.

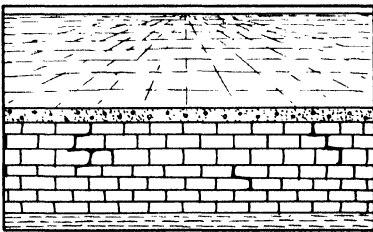
Maturity is marked by maximum dissection by weathering and running water, and in most cases by ice. Little of the original surface remains. Canyons and their tributaries have made great inroads upon the uplifted mass, while, if the region has been glaciated, cirques will have worked back until many of them have intersected, leaving between them sharp peaks and jagged crests—the Matterhorn, Mt. Assiniboine, and the Tetons (pp. 275 and 350) offer good examples.

In the end the mightiest mountain must yield to time and its dual weapons, weathering and erosion. The ruggedness and grandeur which take form in maturity slowly melt away into softer contours, the once-sparkling mountain streams become turbid with their burden of silt, and at last the mountain is brought so low that it is visible only to the eye of the geologist.

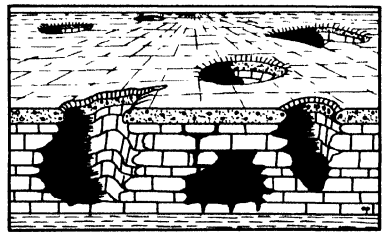
THE CYCLE IN A LIMESTONE REGION

In a few places the dominating erosional force is the solvent action of ground water, the effects of which may be easily followed in the diagram below. The first stages in the development of such a region will resemble those under the influence of surface erosion, as stream valleys soon appear and begin their growth in the usual way. When they cut down to a limestone substratum, however, they begin to find outlets for their waters through underground channels produced by jointing and solution. At this time limestone sinks begin to appear at the surface.

As long as much of the surface remains untouched by either stream valleys or sinks the region may be considered in the stage of youth. But eventually very little of the original surface is left. By this time—the stage of maturity—sinks have become both numerous and large. Adjacent ones have united to form elongated “solution valleys,” which can be distinguished from stream valleys by their irregularity of shape and their steep endings. Natural bridges, formed by the undermining of strips of limestone separating adjacent sinks, are usually present, while beneath the surface the rock is honeycombed with caverns. Surface streams, except short intermittent ones, have disappeared, as a subterranean drainage system has developed which drains off all surplus water. Some of the sinks, however, contain standing water, resulting from the clogging of their outlets by mud.

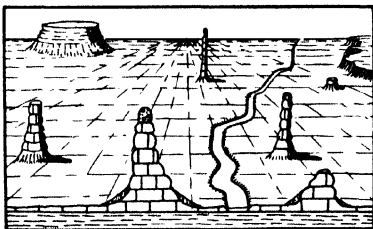


a



b

c



The erosion cycle in a limestone region. Stages are the same as in preceding diagrams.



Canadian Bureau of Geology and Topography

Continental glaciers of the past have smoothed and rounded many aspects of northern landscapes.

Old age is the stage of approaching base level, in this case the lowest level of effective solubility; this may be the level of the water table, or it may be the surface of insoluble rock underlying the limestone. In either case, the surface of the land becomes more and more nearly flat, and less rugged and diversified. Scattered monadnocks may rise above the developing plain. Surface streams now reappear, and stream erosion takes over the task of reducing the region to the level of the sea.

THE CYCLE UNDER GLACIAL CONDITIONS

The progress of erosion by alpine glaciers has already been described in connection with the development of mountain landscapes. Some erosion is effected by the deepening and widening of valleys, but most of it is due to the formation and enlargement of cirques.

In many of the northern parts of the world there remain abundant evidences of unfinished glacial erosion on a continental scale, interrupted by the premature melting of the ice. The distinctive feature of this topography is bluntness of outline. The essence of glacial motion is slow, ponderous, irresistible progress, which acts to reduce all projecting obstacles. Corners are turned only with reluctance; hills are evaded only if they cannot be overridden. Hence the glaciated landscape lacks the sharp outlines, the angles, peaks, and spurs which mark corresponding stages in the erosive work of wind or water.

THE SHORE-LINE CYCLE

Shores of depression. A sinking or recently sunken coastal area will present an intricately irregular appearance; river mouths have become estuaries, hills have been converted into peninsulas or islands. This state is perfectly exemplified by the section of Maine portrayed on the Boothbay, Maine, map (p. 436). The youth of a region such as this will persist throughout the period during which minor changes are being effected in the seaward-lying portions of the coast, while the shore line, protected by these outlying elements, remains little altered.

Water offshore will be deep, and the waves will attack forcefully islands and promontories of the mainland. Seams of weakness will be found, and coves alternating with headlands will be developed. A shore line in this stage is shown on page 224. Cliffs and wave-cut terraces (p. 223) will appear, as will minor features such as stacks, caves, and arches. Headlands will be truncated by wave erosion. The refuse from this wave action will finally accumulate in such quantity that its transportation severely taxes the energy of the waves, and much of the material is dropped in sheltered spots, such as bay heads, where it forms beaches. Spits and bars are formed in many diverse shapes and locations.

By the time of late youth the shore line has undergone much simplification of detail (see Oyster Bay, New York, map, p. 445). Bars have closed the mouths of bays, and have extended themselves in a more or less continuous line from one headland to another. The bays themselves have been filled in with sand washed from the bars or from the mainland or contributed by rivers. Small shore prominences have been ground away.

But the original shore has as yet suffered little dissection. Now the waves attack this section, cutting back the remaining headlands and the sand-choked bays. A prominent sea cliff borders the coast, and no resemblance to the original shore line remains. This may be considered the stage of maturity.

The sea drives the cliff farther inland, broadening the wave-cut terrace, and building a terrace of debris at its outer margin. As the terrace broadens, the retreat of the cliff becomes slower, for the strength of the waves is dissipated on the shallow floor. This may be considered the stage of old age.

Shores of elevation. The initial picture presented by the shore line of a section of coast which has been recently elevated is very different from the one just described. The regions shown on the Tamalpais, California, and Oceanside, California, maps (pp. 448 and 444) are good examples. As the upraised sea floor has but few irregularities, the line of intersection of land and water will be relatively straight. This line should be kept in mind as the original shore line.

Since the water near such a coast line is shallow, waves break at some distance, perhaps a mile or more offshore. Material scoured from the sea bottom beyond the line of breakers is deposited, together with some brought downward by the undertow, forming offshore bars. Smaller waves within the lagoon thus formed reach the shore, and may even cut a line of small cliffs from it. Waves from the sea break over the bars, carrying sand from their seaward to their landward margins, while currents moving shoreward through inlets deposit sediment in the form of deltas. For these reasons the outer edges of most bars of this type are more smooth and regular than those bordering the lagoon.

The lagoon gradually fills with sand washed over the barriers and through breaks in them, with sediment from the land, and with remains of plant life which has established itself in the shallowing water. Both barrier and filled lagoon are eventually destroyed by the waves, which are then free to attack the original shore, thus initiating the stage of maturity. A cliff is formed, headlands and coves develop, and old age comes on, as in the case of the sunken coast, as the waves rasp out a broad terrace which leaves them little strength for further assault upon the coast.

REJUVENATION

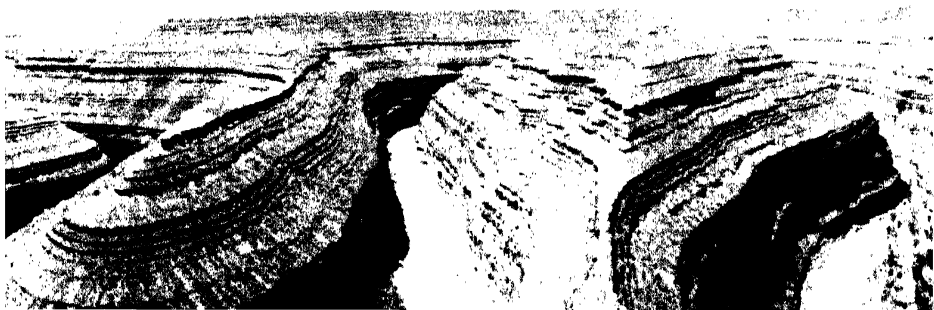
No matter what the agent or agents of erosion that act upon the rocks of any land, the final results must be the same—degradation to a peneplained condition. What then should follow this stage? The logical sequel to peneplanation might appear to be continued gradation until a perfect plane had been achieved. Monadnocks, monuments, irregularities of every sort, it would seem, must eventually succumb to Nature's destroying, though by this time infinitely slow, touch. Rolling plains should flatten out, and even the most minor unevennesses disappear.

But nowhere on the earth do we find the rock surface a perfect plane. Peneplains, indeed, are known, though few of these approach the typical conditions required by theory. We find, rather, land surfaces which in nearly all instances give evidences of having been uplifted before the ultimate completion of their cycle, while there was yet some relief left upon the surface.

Uplift—or the occurrence of any other condition which reinvigorates the forces of erosion—causes *rejuvenation*, which is indicated by

The San Juan River of southern Utah wanders through its fantastic canyon in deeply entrenched meanders. The course followed by the water is approximately six times as long as it would be if the valley were straight.

United States Geological Survey. photograph by La Rue



A well-known example of an antecedent stream is the New River which flows through West Virginia. Its name is an ironical one, for the New is really an extremely old river, having held to its course during the time that the southern Appalachians were rising all around it. The river, eating its way down into the rocks of the valley floor, has not managed to lower its level; instead, the valley floor rose from below while the river, in its erosional efforts, maintained the same level. Sometimes parts of the old valley floor remain as terraces.



Norfolk and Western Railway

an intensification of the attack of the destructive agencies upon the land. Thus an old peneplained region may resume all the typical characteristics of youth, and the cycle start again, with ever-increasing diversification and relief of the landscape.

Evidences of rejuvenation are various. Among them might be mentioned the following:

A dissected peneplain the surface of which has not been entirely destroyed may be represented by the tops of hills all rising to the same height. Many rivers are known which cut through mountain ranges; these *antecedent streams* must have followed their present courses preceding the uplift, erosion keeping pace with the rise of the mountains. A river wandering in wide bends across a peneplain may not straighten itself out upon the initiation of slow uplift, but, having cut its way into hard underlying rock, may retain its meandering course, even though it deepens itself to canyonlike proportions. The meanders of such a stream are said to be *incised* or *entrenched*. The San Juan River, the New River, and the Arkansas River, shown in the photographs reproduced on pages 356, 358, and above, are all antecedent streams. The channel of the San Juan provides excellent examples of entrenched meanders.



Missouri Pacific Railroad

The Royal Gorge of the Arkansas River. The river is an antecedent stream, having cut its great canyon through the mountains as they rose.

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XV · MINERALS



The Greeks of ancient times sought to explain matter in all its complex aspects as combinations in varying proportions of four "original elements"—air, earth, water, and fire. When we, like the Greeks, seek the simplest possible starting point from which to sketch in the picture of the minerals and rocks that make up the earth, we find that the number of elements has grown to more than ninety-six, with names ranging from actinium to zirconium, and with properties almost as diverse as their names. Through these elements, however, runs a thread of unmistakable relationship; the physicist proves the oneness of them all by smashing certain ones and pulling different ones out of the wreckage, and even creating new elements heretofore unknown to the earth. These elements are the raw materials from which our planet is made, and an understanding of their relationships, interactions, and behavior is an essential prerequisite to the task of understanding the rocks and the history that is written in them.

FUNDAMENTAL UNITS AND THEIR REACTIONS

Although the number of elements is relatively small, combinations of them can be effected almost without number. Two or more elements chemically combined constitute a chemical compound, the properties of which are generally entirely different from those of the elements of which it consists. A few of the elements seem incapable of combining in this way. The others can in general be divided into two groups, the metals, or electropositive group, and the nonmetals, or electronegative group. Elements of the first group usually combine readily with elements of the second. Some elements occupy an intermediate position, uniting with members of either group.

When elements combine to form compounds, they always do so in definite proportions by weight. This is because the combination takes place between certain irreducible units of the substances. These units are called *atoms*. The atoms of any element are all exactly alike, except that in some cases they exhibit certain differences in weight

and stability; they are the smallest particles of an element which can retain their identity as such. Actually, they consist of still smaller particles, chiefly electrical in character. The differences between atoms of different elements, as well as the fact that it is now possible to transmute one element into a different one, are to be accounted for by differences in number and arrangement of these subatomic particles.

A system of one- or two-letter symbols has been adopted for the representation of either the elements or individual atoms. Thus the capital letter N stands either for the gas nitrogen or for one atom of nitrogen; Na represents the metal sodium or a single atom of sodium; and Si is the symbol for silicon or for one atom of that substance. Combinations of atoms, whether of the same kind or of different kinds, constitute *molecules*. A molecule can be defined as the smallest particle of matter which can be obtained by physical means—that is, without changing the composition or altering the characteristics of the substance.

Many molecules are very simple in structure, consisting of only a few atoms; for example, free oxygen does not exist in the form of individual oxygen atoms, but as atoms that are connected in pairs, as signified by the formula O_2 , which represents one molecule of the element oxygen. When one atom of the metal sodium (Na) unites with one atom of the gas chlorine (Cl), the resulting molecule is NaCl, or common salt. Similarly, hydrogen combines with oxygen to form water, but in this case two hydrogen atoms are required to form a stable combination with one atom of oxygen, the resulting compound having the formula H_2O . Calcium carbonate, the characteristic constituent of limestone, has the formula $CaCO_3$, which indicates that its molecule is made up of one atom of calcium, one of carbon, and three of oxygen. Some compounds, on the other hand, have very complex constitutions. The molecule of the common mineral hornblende contains forty-three atoms of six different kinds, while some organic molecules may contain as many as fifty to one hundred thousand atoms.

Atoms and molecules often have a strong attraction for others, especially for those of like kind. The tenacity of materials of one kind of matter, such as iron or copper, is called cohesion. The strength of this mutual attraction becomes great only if the attracting particles are very close together. Thus rocks become stronger when under enough pressure to force their molecules into closer proximity to one

another. Broken fragments placed in contact give no evidence of this molecular attraction, for the reason that their rough surfaces do not permit a close approximation of more than a very few of their molecules. It has been found possible, however, to grind metal surfaces so smooth that when brought into contact they can be separated only by the application of force amounting to several hundred pounds to the square inch.

Opposing this tendency of molecules to cling together is the force of the universal movement in which they all participate. In gases, such as the air, the molecules are so far apart (comparatively) that their attraction for each other is small; they therefore move about freely, each traveling at an average speed of about 1500 feet per second, colliding with some 5,000,000,000 other air molecules within that space of time. In a liquid, molecules are much closer together. Water molecules may be thought of as separated by spaces roughly equal to the diameters of the molecules. Because of this close association, molecules in a liquid exert so much attractive force upon one another that exceptional speeds must be attained before they can escape individually from the mass. In solid substances this cohesive force is very great indeed; a force of nearly fifty tons is required to tear apart the molecules in a one-inch bar of steel. Nevertheless, the molecules of a solid are in rapid motion, presumably vibrating in more or less fixed positions, rather than moving about freely within the mass. The densest solid is mostly empty space, its vibrating particles accounting for but a small part of its volume.

The *heat* that a substance possesses consists of nothing more nor less than the motion of its constituent particles. Temperature can be considered a measure of molecular motion. The state in which a body exists—as a solid, a liquid, or a gas—is determined by the relative effectiveness of molecular cohesion and of molecular motion, and by the effects of outside pressure. In substances that are solids at ordinary temperatures, cohesion prevails over the disruptive tendency of the molecules to scatter. If sufficient heat is applied, the movement of the molecules is increased to a point at which it partially overcomes the cohesive force, and the solid, unable to maintain its shape, melts. At still higher temperatures this force is counteracted entirely, and the molecules fly off into space, in that condition constituting a gas or vapor.

Pressure lowers the freezing (melting) points of substances which expand upon freezing, and raises the freezing points of those which contract. Most rocks and metals contract upon solidification from a molten condition; under pressure, therefore, the melting points of such materials will be raised. Water and a number of other substances expand upon passing from the liquid to the solid state; hence increased pressure permits freezing in these cases only at lowered temperatures.

Pressure also, by restricting molecular movement, hinders the change from the liquid to the gaseous state. Evaporation of a liquid, therefore, is more rapid under reduced pressures and slower when pressures are high. The boiling point of a liquid is the temperature at which the pressure exerted by its escaping molecules becomes equal to the confining pressure of the air or other gas above the liquid. When this equilibrium is established, evaporation proceeds rapidly.

CRYSTALLIZATION

Not only do like molecules have a strong attraction for each other, but this power of attraction acts in certain definite directions in each kind of molecule. As a result, when molecules are pulled close together in one way or another, they almost always arrange themselves in such a manner as to conform to a definite pattern, which is characteristic of the substance in question. The process of union of molecules of the same kind and their orientation into an orderly configuration is known as *crystallization*, and the substances having such an orderly internal arrangement are said to be *crystalline*. Since fully ninety-five per cent of all the rocks of the earth's crust have a crystalline structure, a clear understanding of the process of crystallization is of the utmost importance in gaining an insight into how the earth is put together.

Let us note what is happening in a solution of salt in water, which is slowly evaporating. In this solution the salt molecules are dispersed among the molecules of water, and many of them have broken up into their atoms of sodium and chlorine. As the water evaporates, the salt molecules and their component atoms are brought gradually closer together, until at length their mutual attraction makes itself felt. The molecules begin to take positions in close proximity to one another, but this action does not take place in a haphazard or fortuitous man-



Illinois Geological Survey

Crystals of fluorite (calcium fluoride). These well-formed cubes were deposited from water. From the collector's point of view, fluorite is one of the most interesting of minerals, occurring not only in perfect crystals of large size but also in almost every imaginable color—white, yellow, green, blue, violet, and red. Many specimens exhibit the phenomenon of fluorescence.

ner. The atom of sodium is positively charged, the chlorine atom negatively. Since like charges are mutually repellent and unlike charges attractive, sodium atoms will not take up positions adjacent to other sodium atoms, but will so orient themselves that they are next to atoms of chlorine. The latter, similarly, will be attracted to sodium atoms and repelled by chlorine atoms. Hence the salt granules (crystals) which can be seen forming in the brine consist of alternating sodium and chlorine atoms arranged in rows extending in three directions at right angles to each other. Deposition of solid matter from solution in the manner described is one of the commonest ways in which crystallization can be brought about. Cubic crystals formed in this way are shown above and on page 366.

Or let us imagine what is happening in a mass of molten rock buried deeply in the ground and cooling slowly. At first molecules speed past one another at such rates that their cohesive tendencies have no opportunity to assert themselves, but as cooling continues a point is finally reached at which their free motion is restricted, and they begin to assume definite positions with relation to one another. Molecules of like kind begin to collect into groups, their atoms taking up positions determined by the locations of other atoms in the group. Since free movement in the mass of rock has ceased, the rock is no

longer in a liquid state. The solidified groups of molecules of the same kind are called *crystals*.

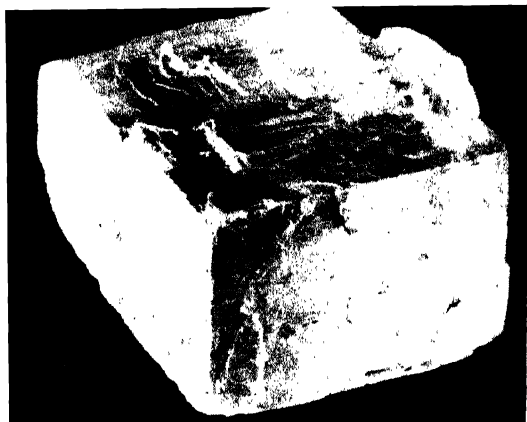
It will be seen that slow cooling favors the growth of large crystals, since it permits a long interval to elapse between the time at which molecular motion has slowed sufficiently for mutual attraction to become effective and the time when the mass becomes so viscous that the free movement of the molecules is impeded. Huge crystals of beryl have been found in New England, some of them measuring eighteen feet in length and four feet in diameter.

If a molten mass cools very rapidly, as when it is disgorged by a volcano upon the surface of the land or poured out under the sea, the jumbled assemblage of molecules may be brought into positions of stability before any separation into homogeneous groups has had time to occur. The resulting rock then shows no crystalline structure, for the disorganized molecules are scattered about with no semblance of system; the rock is a natural or volcanic glass. A noncrystalline material of this kind is said to be *amorphous*.

The cooling of a gas or vapor may so decrease the speed of its molecules that they cohere into crystals without the intervention of the liquid state. Thus steam striking a cold object may crystallize into frost, as shown on page 367. Sulfur vapor escaping from hot rocks in the depths of the earth may similarly condense into crystals of sulfur.

It should be pointed out that crystalline structure does not necessarily imply the existence of crystal form. A crystal is a discrete body having characteristic shape and bounded by plane surfaces. Crystalline structure means an orderly internal arrangement of the constituent molecules, but not necessarily a definite external shape. Well-formed crystals are relatively rare; their development depends not only upon ample time for growth, but upon freedom from undue crowding, a condition seldom realized during rock formation. A comparison of the illustrations shown on pages 22, 364, and 366 with those on pages 376 and 379 will make the effect of crowding clear.

If X rays are passed through crystalline material, they are deflected by the regular rows of molecules, like light passing through a window screen. A glassy substance, on the other hand, allows the passage of the rays without significant effect. By this means the crystalline structure of a broken fragment of crystal or a mass in which insufficient space prevented the development of discernible crystals can be demon-



Ward's Natural Science Establishment, Inc.

Halite (sodium chloride or common salt), showing cubic cleavage. Salt crystals form from water solutions as sodium and chlorine atoms are laid down in alternate and very regular rows; cleavage is the result of weakness along these rows of atoms.

strated, and thus distinguished from the amorphous structure of a piece of glass.

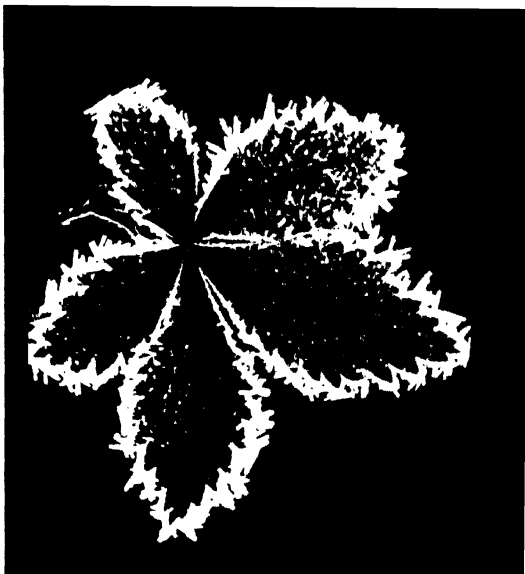
Some, though not all, crystalline materials exhibit the property known as *cleavage*, which can be defined as the constant tendency to break along plane surfaces, the positions of which are determined by the arrangement of the molecules. Amorphous substances never exhibit true cleavage, although they sometimes tend to split in a regular manner as a result of pressure or other outside forces.

The shape assumed by a crystal is controlled in part by its composition, in part by external conditions. In the case of common salt, of which the molecule consists of but two atoms, we have seen that crystal growth may proceed along three axes, all at right angles to each other. It could almost be predicted, therefore, that crystals of this substance would be cubic in shape, which is in fact the case. When a salt crystal breaks, furthermore, it exhibits cubic¹ cleavage, splitting along the rectangular rows of atoms. In the salt cube pictured above this rectangular cleavage is plainly shown, not only in the shape of the entire specimen, but by the shape of small fragments which have been chipped off, some of which are visible on the upper surface.

Water, as is well known, crystallizes into six-sided figures. The hexagonal shape of the ice crystal is undoubtedly connected with the fact that the water molecule is made up of three atoms. In general it may be said that a complex crystal form is usually associated with a complex molecular composition. Some crystals have eight sides, some twenty-four, some forty-eight. Some are built around axes that

¹The term *cubic* as used in this connection does not imply equilateral solids, but merely figures bounded by six faces parallel or at right angles to one another.

Crystallization sometimes takes place as gases pass directly into the solid state. The illustration shows the effects of heat radiation at low temperatures from vegetation. Frost may form on any sort of material which radiates heat rapidly, as the result of the condensation of moisture from the air. Snow crystals also result from the condensation of water vapor in the atmosphere at below-freezing temperatures.



United States Weather Bureau, photograph by W. C. Bentley

are placed at right angles, some around axes that are inclined at various angles to one another. Some substances assume more than one crystal form, depending upon the conditions of their formation. Calcium carbonate, for example, very frequently appears as rhombohedrons—six-sided solids whose faces are not at right angles—but it may crystallize into any of more than 300 different shapes.

That the composition of a crystal is not the sole determinant of its shape is easily seen in the crystal habit of the common element carbon. When this substance crystallizes under ordinary pressures it occurs as the soft material known as graphite, but when crystallization occurs under the tremendous pressures generated by the cooling of iron-bearing rocks of volcanic origin, the carbon is cast in the denser, extremely hard, octahedral form which we know as diamond.

THE FORMATION OF MINERALS

The great bulk of the earth, at least near the surface, is made up of an amazingly small number of elements. Several thousand analyses show the outer ten miles of rock, plus the atmosphere and the water of the earth, to consist of the following elements in the designated proportions:¹

¹F. W. Clarke and H. S. Washington, *The Composition of the Earth's Crust*. United States Geological Survey Paper 32 (1924).

Element	Per Cent	Element	Per Cent
Oxygen	49.52	Hydrogen	.88
Silicon	25.75	Titanium	.58
Aluminum	7.51	Chlorine	.188
Iron	4.70	Phosphorus	.12
Calcium	3.39	Carbon	.087
Sodium	2.64	Manganese	.08
Potassium	2.40	Sulfur	.048
Magnesium	1.94	All others	.167
			<u>100.000</u>

As will be seen from this table, the two elements oxygen and silicon constitute more than three fourths of the raw materials of the earth's surficial rocks. If to them we add aluminum, iron, calcium, sodium, potassium, magnesium, and hydrogen, we have a list that represents well over 98 per cent of the whole.

Beginning with this small group of elements, we can deduce from a knowledge of their chemical behavior the probable early steps in the formation of the earth. Oxygen is not only the most abundant element in the earth's crust, but it is one of the most active—that is, it combines readily with other elements. It belongs, further, to the group of non-metals, while almost all the other elements listed in the foregoing table act as metals. We may assume, then, that one of the first large-scale chemical reactions to take place was the combination of oxygen with the silicon, aluminum, iron, and other metallic elements. The compounds thus formed are known as oxides, and are named individually silicon dioxide, aluminum oxide, iron oxide, and so forth. The most abundant of the oxides, as shown by analyses of the rocks, are listed in the following table:¹

Compound	Percentage (of crustal rocks)	Compound	Percentage (of crustal rocks)
Silicon dioxide	59.85	Calcium oxide	4.81
Aluminum oxide	14.87	Magnesium oxide	3.77
Iron oxide		Sodium oxide	3.29
Ferric	2.63	Potassium oxide	3.02
Ferrous	3.35	Hydrogen oxide (water)	<u>2.05</u>
			97.64

¹F. W. Clarke and H. S. Washington, *The Composition of the Earth's Crust*. United States Geological Survey Professional Paper 32 (1924).

The next important step in the evolution of the earth's materials consisted of combination among these oxides. From the standpoint

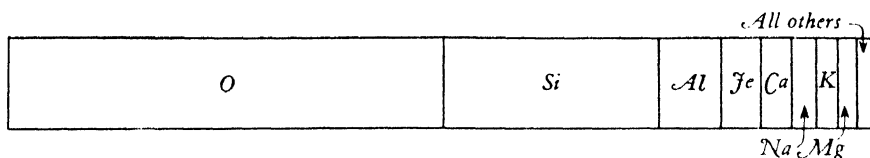


Diagram showing relative proportions of elements forming the earth's crust.

of chemical activity, we find here a situation very similar to that which existed among the original elements. An oxide which upon dissolving in water produces an acid is classed as a nonmetal, while one which dissolves to form a base—a substance with properties which can be considered opposite to those of an acid—acts like a metal in its chemical relationships. Acids do not react with acids, or bases with bases; rather, bases react with acids to form a third class of substances, known as salts.

When we examine our list of principal oxides we find that one, the abundant oxide of silicon, is to be classed as an acid-former, corresponding to oxygen among the elements; while the others act chiefly as bases, with the exception of hydrogen, which is neutral. Silicon dioxide, therefore, would enter into combination with the basic or metallic oxides, producing through this union the great family of salts known as *silicates*, which have been said to make up fully nine tenths of the earth's crust.

Certain other compounds occur on a minor scale. Carbon dioxide, another of the acidic oxides, combines with various metals to form the group of salts known as *carbonates*. Sulfur combines in the same way, producing *sulfides* or, if in combination with oxygen in addition to a metal, *sulfates*. Chlorine and a small number of other elements also form compounds with the metals.

These oxides, silicates, and minor compounds, together with such elements as have remained uncombined, are (unless gaseous at ordinary temperatures) designated as *minerals*. A mineral may be defined as an inorganic solid or liquid of definite composition occurring naturally in the earth. This definition requires a little qualification, however, since in many minerals certain elements may be present interchangeably, either to a limited or to an unlimited extent. Thus a formula

such as Zn, FeS means that either of the metals—in this case zinc or iron—can be combined atom for atom with the nonmetal. Minerals of this kind are called *isomorphous* minerals; they differ from real mixtures in that they can be represented by chemical formulas, while ordinary mixtures, which do not involve any chemical combination of atoms, cannot be so represented.

Well over 1000 distinct minerals are known to exist; new ones are discovered from time to time, and occasionally old ones are discredited as individual species. Perhaps about fifty minerals may be considered common enough to have a place in the study of general geology. Most of these can be recognized easily by means of their physical characteristics. The following properties should suffice for the identification of almost all minerals likely to come to the attention of the beginning student:

1. *Crystal form.* The typical crystal shapes of many minerals are often an important factor in their identification.

2. *Structure.* Minerals differ widely in gross structure, occurring in forms that are described as massive, fibrous, columnar, and the like.

3. *Color.* Color in some minerals is a more or less constant character, but in some it is quite variable.

4. *Streak.* The color of a mineral when in a finely powdered condition is called its streak. The streak is usually observed by rubbing the mineral on a piece of rough porcelain. In many cases it is a much more reliable property than color.

5. *Luster.* Minerals differ in the way they reflect light, appearing as a consequence glassy, pearly, resinous, earthy, etc.; these and similar terms are used to describe the property known as luster. An opaque mineral with a black or a very dark streak is said to have a metallic luster.

6. *Cleavage.* The type of cleavage, or ability to break along plane surfaces, of a mineral is often a very useful aid in its identification. Cleavage may occur in one plane only, or in several planes, which lie at certain definite angles to one another. A mineral which does not split in this manner is said to possess fracture, which may be described as irregular, splintery, hackly (with sharp edges), or conchoidal (exhibiting smooth curved surfaces).

7. *Hardness.* Hardness, which is one of the most useful of all prop-

erties in the identification of minerals, is the resistance offered to scratching, and can be measured roughly by scratching one mineral upon another, or upon substances of known or standard hardness. Superior hardness is indicated if a mineral leaves a mark which will not rub off. The relative hardness of a mineral is expressed by a number which indicates its position with reference to a group of minerals constituting the "scale of hardness"; these minerals, beginning with the softest, are as follows:

1. Talc	3. Calcite	6. Orthoclase	9. Corundum
2. Gypsum	4. Fluorite	7. Quartz	10. Diamond
	5. Apatite	8. Topaz	

The hardness of the softer minerals (which include the majority of common forms) can often be determined with accuracy sufficient for most purposes by testing with the fingernail (hardness $2\frac{1}{2}$), a cent (H. 3), a knife blade (H. 5 to $5\frac{1}{2}$), and window or bottle glass (H. $5\frac{1}{2}$).

8. *Specific gravity.* The specific gravity of a mineral is the ratio of its weight to the weight of an equal volume of water. Thus the specific gravity of galena, the sulfide of lead, is 7.6, while that of gold approaches 20. The specific gravity of most minerals, however, lies between 2 and 4, so that the usefulness of this characteristic in identification, especially in the field, is rather limited. Accurate determinations, however, can be made in the laboratory.

COMMON MINERALS

The oxides. As shown by the table on page 368, the preponderant elements oxygen and silicon in combination with each other account for nearly 60 per cent of the mineral matter of the earth's crust. For the most part these associated elements occur combined with others, in the form of silicates, but a large amount of free silicon dioxide (silica) remains in excess of that used up in silicate formation; this free silica constitutes one of the most common and widely distributed of all minerals, comprising about 12 per cent of the earth's crustal rocks. In solid form it is called *quartz*.

Clear, glassy hexagonal crystals of quartz (p. 22) are often called rock crystal. This mineral also occurs in massive forms. Quartz is one of the hardest of the common minerals (H. 7). It has no cleavage,

but fractures along slightly curved surfaces. It appears in many different colors—white, red, yellow, purple, black. The cause of this coloration is unknown; it is probably due to optical factors in most cases, rather than to included impurities. More than two hundred varieties of quartz are recognized, among them amethyst, jasper, carnelian, agate, chalcedony, and flint.

Water, the oxide of hydrogen, is geologically a most important mineral because of its solvent and chemical powers, and because of its mechanical effects upon the earth's surface. Among other important minerals of the oxide group, several oxides of iron deserve mention. Of these *hematite*, the "red iron oxide," is of paramount economic significance, being the chief commercial source of iron. Its formula is Fe_2O_3 . Hematite varies in color from black to red, and may exhibit a luster that is either metallic or earthy. Its most constant feature is probably its Indian red streak. *Göthite* and *limonite* are closely associated hydrous (water-containing) iron oxides, yellowish brown to dark brown in color, and having yellow-brown streaks. They are usually easily recognizable by their typical "iron rust" appearance, although difficult to distinguish from each other in the field, where they are both generally called "limonite." *Magnetite*, Fe_3O_4 , occurs massive or in octahedral crystals. It is black, heavy, and too hard to be scratched with a knife; its most striking characteristic is its pronounced magnetic property.

Silicates. There are so many silicate minerals that only a few can be treated here, and these chiefly as groups rather than as individual species. The reason that such a comparatively small number of oxides can unite to produce such a very large number of silicates is that the silicates in almost all cases are not distinct, specific compounds, but isomorphous mixtures; that is to say, they grade into one another in composition.

The amount of silica present in a silicate bears a relation to the kind of metallic oxide with which it is combined. Thus the silicates of potassium, sodium, and calcium (the salic group) are high in silica; these minerals are consequently relatively light in weight and in color, lending these characteristics to the rocks of which they form a part. Silicates of iron and magnesium (the ferromagnesian group) are less rich in silica than the salic minerals, and are more dense and of a

darker color. This variation in silica content is the most significant feature of these minerals, in so far as their rock-making properties are concerned, and a working knowledge of it is fundamental to a clear understanding of their varied associations.

The *feldspars* comprise a large group of silicates of the salic type. Those containing maximum quantities of silica are called orthoclase feldspars; they are silicates of potassium and aluminum, having the ideal formula KAlSi_3O_8 . In color these minerals are commonly pink, red, white, yellow, or gray, and they exhibit cleavage in two planes which are at right angles to each other. The *plagioclase feldspars*, so called in reference to their cleavages, which are not at right angles, form an isomorphous series from a sodium aluminum silicate ($\text{NaAlSi}_3\text{O}_8$) to a calcium aluminum silicate represented by the formula $\text{CaAl}_2\text{Si}_2\text{O}_8$. The plagioclases, which otherwise often resemble the orthoclases, may frequently be recognized by the presence of fine striations on certain of their cleavage surfaces.

As will be noted from their formulas, orthoclase contains more silica than plagioclase, the amount decreasing through the plagioclase series.

The *micas* are well known for their perfect cleavage in a single plane, their transparency, and their flexibility. The light-colored micas (muscovites) are silicates of potassium and aluminum; the dark ones

Calcite in the form of rhombohedral crystals. Few minerals surpass calcite in the splendid development and amazing variety of its crystals. Calcite's unusually wide distribution is the result of its high solubility in water containing carbon dioxide, and the ease with which it is deposited when the carbon dioxide is lost. Its crystalline form is commonly found in metallic ore deposits, being often associated with lead, zinc, copper, and silver minerals. It occurs in veins, in rock fissures, as cave deposits, and in definite beds.



(biotites) contain in addition magnesium and iron, the latter accounting for their black or brown colors.

The important *amphibole* and *pyroxene* groups consist of silicates of ferromagnesian composition. The most common member of the amphibole group is the mineral *hornblende*, while *augite* is the commonest representative of the pyroxenes. Hornblende and augite, both very dark in color and of complex composition, are often quite difficult to distinguish.

Another important ferromagnesian mineral is *olivine*, an isomorphous mixture of iron and magnesium silicates. It is greenish in color, and often has a granular texture.

The minerals known collectively as *chlorite* are hydrous silicates of aluminum, iron, and magnesium, and are always alteration products of other silicates. They are of about the same hardness as the fingernail or a little softer, green in color, usually rather dark; they cleave in thin sheets resembling mica, from which they can be distinguished by their lack of flexibility.

Kaolinite is a hydrous aluminum silicate ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), and is the principal constituent of clay (kaolin). When pure it is soft, white, and earthy, and is used in the manufacture of chinaware. Kaolinite results from the action of water and carbon dioxide on feldspar.

Talc is a hydrous magnesium silicate ($\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$), and is a prominent mineral in some types of rocks. It is characterized by softness and a greasy feel. Some forms are known as *steatite* or *soapstone*.

Other minerals. Far less abundant than the oxides and silicates but still of noteworthy importance are a number of minerals belonging to the carbonate, sulfate, chloride, and sulfide groups. *Calcite* is a white or light-colored, sometimes transparent mineral which crystallizes in a great variety of forms. In composition it is calcium carbonate, CaCO_3 ; it is a little harder than the fingernail, and effervesces readily with a cold acid, yielding carbon dioxide. Calcite in one of its commonest crystal forms is shown in the illustration on page 373. *Dolomite* is calcium magnesium carbonate, and closely resembles calcite; it is not rapidly attacked by cold acids, however, unless in powdered form, but effervesces with hot acid.

Gypsum is hydrous calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). It is quite

variable in color, but is commonly white or gray. In structure it is frequently massive, but also occurs in a number of interesting crystal forms. Gypsum is usually easy to identify by its unusual softness (H. 2—softer than the fingernail).

Halite (salt) is recognized by its taste and its tendency to crystallize and cleave into cubic forms.

Pyrite, commonly called fool's gold, is a sulfide of iron (FeS_2). It is hard, brittle, and pale to dark yellow in color. It may be granular or massive; crystals, usually striated cubes, are common. Its streak is black. Pyrite is widely distributed, and is the most common example of the sulfide minerals.

The minerals described, plus a few other silicates and other compounds of lesser importance, comprise something like 99.5 per cent of the rocks of the earth's crust. Among the remaining one half of one per cent, however, are minerals which possess an importance out of all proportion to their abundance. Among these are to be found the metallic ores—native gold, silver, copper, and platinum; the sulfides of lead, zinc, copper, and silver; and many other compounds of the greatest value to man. These minerals as they ordinarily occur in the rocks are present in only the most insignificant quantities; they are found in appreciable amounts only as a result of concentration by water or some other agency.

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XVI • ROCKS



Of the large number of elements, compounds, and isomorphous groups that constitute the minerals of the crust, only seven or eight can be considered of importance in the formation of rocks; these few, indeed, make up practically the whole of the rocks of the earth. Unlike minerals, rocks do not have definite compositions. With minor exceptions they consist of mixtures of minerals, which may be present in any proportions. Some of these combinations are more common than others, and these—about 600 in all—have received specific rock names.

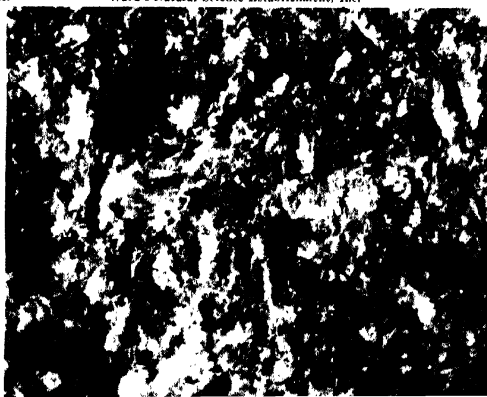
The classification of rocks presents many difficulties. Nature has set no such sharp metes and bounds as in the organic world. In practically all of the particulars by which petrologists seek to classify them, rocks grade into one another; not only so, but in the process of adjustment to their environment they universally undergo alterations of both composition and texture. It is hardly surprising, then, that much disagreement exists among experts as to the best manner of naming and classifying the rocks of the earth.

The plan adopted in this volume is one intended to serve the purposes of the student who has access neither to microscope nor to chemical analysis. Distinctions depending upon the identification of minerals which can be recognized only in the laboratory, or upon mathematical percentages of ingredients, will be avoided as much as

(Left) *A porphyry, showing conspicuous phenocrysts embedded in fine-grained basalt.* (Right) *Granite, a coarse-grained siliceous rock, and the best-known of the igneous rocks.*

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possible. For the student who wishes to know and enjoy such rocks as he picks up in the field, any useful classification must be based, in so far as is consistent with accuracy and generally accepted thought on the subject, upon characteristics which he can observe directly, or which he can infer from such factors as color or mineral association.

THE IGNEOUS ROCKS

As a hot magma gradually cools, some of its constituents tend to differentiate, the lighter, more siliceous minerals separating somewhat from those of basic or ferromagnesian composition. A further differentiation occurs with respect to the texture of the minerals, its nature depending in part upon the composition of the material, but largely upon the rate at which it solidifies. Rocks which have cooled deep within the earth (plutonic rocks) will exhibit coarsely crystalline structure, whereas those which have been expelled upon the surface (volcanic rocks) will consist of much smaller crystals, or perhaps of none at all.

Classification of igneous rocks is based upon the two characteristics of *composition* and *texture*. While the texture of a rock is evident to the eye, its composition is often much more difficult to determine. Valuable clues to the identification of certain rock-forming minerals may be obtained, however, from an understanding of the ways in which such minerals are commonly associated with one another. If free quartz is present in a rock, for example, the observer may infer that the magma from which the rock was formed contained silica in excess of that required to form silicates with all the metals present; under these conditions the feldspars formed would ordinarily be those of maximum silica content—that is, the orthoclases. In the formation of a small number of rocks, there was just enough silica present to form orthoclases, but none left over to crystallize into free quartz; but usually if the rocks are light colored but contain no visible quartz, the feldspars present may be assumed to be plagioclases, since these are less rich in silica than the orthoclases. If rocks are of a dark color, a deficiency of feldspars is indicated, and the rocks probably consist chiefly of minerals of the ferromagnesian type.

In the order of decreasing silica content, then, we may arrange most of the ordinary igneous rocks into five major groups:



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Obsidian, a volcanic glass which forms upon very rapid solidification of acidic lavas. This specimen exhibits typical conchoidal or shell-like fracture. Few obsidians are as completely vitreous as this; most specimens contain small quartz, feldspar, or ferromagnesian crystals. Those which contain minute crystals may have a pitchy or resinous luster.

1. Those containing free quartz, orthoclase feldspars, and subordinate quantities of ferromagnesian minerals.
2. Those containing little or no free quartz, but otherwise resembling group 1.
3. Those consisting of plagioclase feldspars of the more siliceous kinds (largely sodium silicates) and ferromagnesian minerals, hornblende usually predominating.
4. Those in which the plagioclases are of less siliceous type (calcic), and usually of diminished quantity, and in which the ferromagnesian minerals are commonly pyroxene and some olivine.
5. Those consisting predominantly of ferromagnesian minerals.

The relationships and identifying characteristics of these fundamental rock-making minerals are shown in Appendix B, p. 423.

Rocks which cooled so slowly that their constituent minerals are easily discernible to the unaided eye are known as phanerites; those consisting of very small or microscopic crystals are aphanites. If cooling has been very rapid, especially in the case of the more siliceous magmas, crystal formation may have been completely inhibited, and the resulting rock is a volcanic glass or *obsidian*. A *porphyry* is a rock typified by the presence of notably large crystals (*phenocrysts*) embedded in a groundmass of smaller crystals or of volcanic glass. This structure, which is illustrated on page 376, can be explained upon the assumption that while the magma was still deeply buried the phenocrysts formed, growing slowly to large size, and that the magma was later moved toward or ejected upon the surface of the ground, cooling so suddenly that the remaining liquid solidified into an apha-

nitic or glassy groundmass. This explanation does not appear applicable to all cases of porphyritic structure, however.

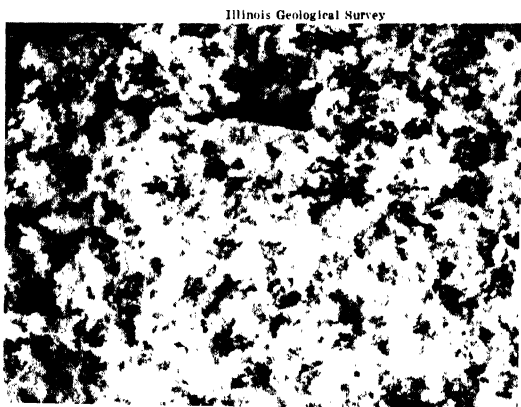
Granite, rhyolite, and obsidian. *Granites* (group 1, above) are coarse-grained representatives of those rocks which have solidified from a magma containing more than enough silica to form silicates with all the available metals; consequently quartz, which can be recognized in a specimen by its glassy or greasy luster and lack of cleavage (see page 370), is present in conspicuous amount. The more highly siliceous feldspars are also abundant. In addition to orthoclase feldspar, which is often flesh-colored or reddish, some light-colored plagioclase may be present. (If feldspars of different colors are found in close association, one is in all probability an orthoclase, the other a plagioclase.) Small amounts of ferromagnesian minerals, ranging around 10 per cent, occur in granites. Mica, usually biotite, is the mineral of this type most frequently encountered, although hornblende may supplement or replace it.

During the process of solidification of granite, crystallization of the different minerals proceeds at different rates. First to crystallize out of the magma are the ferromagnesian minerals, next the feldspars, and last of all the quartz. For this reason granite often exhibits perfect crystals of hornblende, crystals of feldspar which have been distorted because of crowding, and crystalline quartz which shows little indication of typical shape.

Rhyolite, of the same composition as granite, has cooled much more rapidly. As a result, it lacks conspicuous crystals, and has a homogeneous or fine-grained appearance. This rock is light colored, and may show a streaked or banded structure (flow structure).

Obsidian, the volcanic glass that results from very rapid cooling, is usually black, probably because of the presence of minute scattered particles of magnetite, indicating an incipient state of crystallization;

A light-gray diorite. Diorite is an intrusive rock, and therefore coarse-grained. It is classed in between the extremely acidic and extremely basic igneous rocks, containing neither quartz nor orthoclase feldspars.



sometimes these grains have apparently been oxidized to hematite, giving the rock a reddish color. Obsidians usually correspond to granite rather than to the darker igneous rocks in composition, for the reason that magmas of this type become so extremely viscous during rapid cooling, and this viscosity frequently hinders molecular movement sufficiently to prevent crystallization. The color, type of fracture, and something of the luster of this interesting rock may be observed in the illustration on page 378.

Syenite and trachyte. These rocks, which are relatively rare, form from those magmas in which the amount of silica present is just about equal to or but slightly in excess of that required for the formation of orthoclase. They therefore contain orthoclase, but little or no free quartz (group 2, p. 378). Some of the more siliceous plagioclases are usually present also. Ferromagnesian minerals, which are not sufficiently abundant to produce dark coloring, are similar to those of granite.

Syenite is the coarse-grained representative of this group, *trachyte* the fine-grained one. Trachyte is in many cases indistinguishable from other light-colored, fine-grained rocks, such as rhyolite, except through the employment of chemical or microscopic tests.

Diorite and andesite. Diorite is a coarsely crystalline rock in which the available silica was insufficient to produce either quartz or orthoclase feldspars. The feldspars, therefore, will be plagioclases, which can often be identified by their striated cleavage planes; they may also exhibit a platy or lathlike structure. These plagioclases will be chiefly sodium silicates. Hornblende is the most characteristic ferromagnesian mineral.

The fine-grained equivalent of diorite is the rock *andesite*, so named from its widespread occurrence in the Andes Mountains. These rocks (group 3) are darker in color than those previously described, because of their decreased silica and increased ferromagnesian content.

Gabbro and basalt. Plutonic rock consisting of plagioclase feldspars (chiefly of the calcium silicate type) and predominating quantities of ferromagnesian minerals (characteristically pyroxene) is called *gabbro*.

It is coarse-grained, dark in color, and heavier than such rocks as granite and syenite. It is sometimes difficult to distinguish from diorite.

Fine-grained, dark-colored rocks having the composition of gabbro are called *basalt*. This type of rock is seen in many lava flows. See group 4.

Peridotite. The term *peridotite* is applied to rocks consisting almost entirely of ferromagnesian minerals (group 5), and especially to mixtures of pyroxene and olivine. Rocks consisting principally of pyroxene are distinguished as *pyroxenite*, and those chiefly of olivine as *dunite*.

Fine-grained rocks of this character are called basalts, which thus becomes a collective as well as a specific term; they are also often referred to as trap.

THE SEDIMENTARY ROCKS

The term *sedimentary*, as used to denominate one of the classes of rocks, is somewhat too broad for its implications. In addition to rocks formed by the consolidation of mineral matter which has settled out of water or air, this class is defined to include a number of products of crystallization from either water or air—but not from magma—and also certain rocks of organic origin.

Rocks formed from particles broken or weathered from pre-existing rocks are referred to as clastics, while those which have resulted from chemical precipitation from solution are sometimes called “evaporites.” No term designating the organically formed rocks has found general acceptance.

The classification of sedimentary rocks, like that of the foregoing class, is based upon both texture and composition. The disintegration of igneous and other rocks sets free particles of various sizes and kinds. Quartz, being an uncommonly hard and resistant mineral, generally remains in masses of such size as to be considered pebbles, gravel, or sand; softer minerals, such as feldspars and other silicates, usually become reduced to a much smaller size, and are classified as silt, mud, or clay. While the classification of these particles is a purely arbitrary matter, the following table will give some idea of the relative and actual sizes of the grains which constitute the common sedimentary rocks:

Fragment	Diameter in Millimeters	Fragment	Diameter in Millimeters
Boulder	250 or more	Sand	.06 to 4
Cobblestone	64-250	Silt	.005-.05
Pebble	4 to 64	Clay	Less than .005

Characteristics of Sediments

Composition and texture. The characteristics exhibited by the particles making up a sedimentary rock generally tell an interesting story in themselves. Their composition and sizes are largely determined by such factors as the nature of the parent rock, the amount and kind of transportation which has preceded deposition, the kind of climate prevailing during the disintegration and reassembling of the rock, and the physiography of the region involved. A careful study of sedimentary rocks from these standpoints may reveal many of the conditions attending their formation.

Generally speaking, the less thorough the weathering and the shorter the distance over which the weathered material has been moved, the more nearly will the composition of a deposit resemble that of the rock from which it has originated. Sand containing an exceptionally large proportion of quartz points to an origin marked by slow weathering in a moist, warm climate, and probably to a long, wearing journey. The presence of softer minerals of coarse size in conspicuous amounts suggests little transportation, while large quantities of material of a decomposable nature are to be expected only under conditions of mechanical weathering such as obtain in arid regions. The presence of undecomposed feldspar in deposits of sand is often accepted as evidence of aridity at the time of deposition, although the somewhat stable nature of feldspar renders such evidence less conclusive than is generally supposed.

The destruction of granite yields much greater quantities of silt and clay than of sand, and associated deposits of the latter materials in which particles of the finer sizes definitely predominate suggest a granitic parent rock. The presence of certain minerals which are produced only by the forces of metamorphism indicates that the source of the sediments in question is to be sought in such rocks as gneiss or schist (p. 289); garnet, for example, is never originally a constituent

of igneous or sedimentary rocks, but is formed during metamorphic changes.

The shapes of sedimentary particles are also significant, as has been explained in connection with water- and wind-transported materials. However, the great majority of deposits consist of materials derived from several sources, each of which will have left its influence on some of the grains. The angularity as well as the size of the particles decreases with the thoroughness of the weathering and with the distance from the source of supply.

Thick deposits of coarse sediments indicate that highlands of some sort adjoined or were near the sites of deposition, while extensive accumulations of mud mean that the land masses from which they were derived were but little elevated.

Stratification. Stratification is an important characteristic of the majority of the deposits made by wind or water. Strata are marked by differences in texture, color, or composition, and owe their presence in a deposit to changes in the conditions attending sedimentation. Stratification may be the result of seasonal changes in rainfall, of storms, or of fluctuations of sea level.

Sedimentary layers are separated from one another by *bedding* or *stratification planes*. They may be only a fraction of an inch in thickness, or they may be many feet. Very thin strata are called *laminae*, and formations of such strata are described as *laminated*.

As mud dries, it shrinks—often producing deep cracks like those in the illustration. When these cracks occur in ancient rocks, they are good evidence that the rocks were laid down under shallow water conditions—flood plains, deltas, or coastal flats which were dried, cracked, recovered with water and the cracks filled with new sediment. Sometimes the surfaces of the cracked blocks wrinkle up and form hard pellets which may be incorporated into a kind of conglomerate.

The Earth Science Digest, photograph by W. D. Keller



Special markings. The conditions under which certain sediments have been accumulated are sometimes clearly revealed by special imprints left upon them. The footprints of animals or the imprints of leaves or other bits of vegetation made in damp mud which is thereafter exposed for a considerable period to the sun may be preserved if soon covered by silt or wind-blown sand. The impressions of rain-drops may be preserved in a similar manner. Expanses of mud, upon drying, often crack into polygonal figures, which may or may not wrinkle up on the surface. When these cracks are thoroughly dried and hardened, they may be filled with fine sediments and covered.

Since such markings as these owe their formation to the capacity of mud to shrink and harden while drying out, their presence indicates continental rather than marine deposition. They are formed principally along the shores of shallow lakes which are affected by seasonal changes in rainfall, shrinking in area during the drier parts of the year. They are of common occurrence also on the flood plains of rivers, and along the landward portions of deltas. Tidal flats seldom give rise to these structures, partly because they are often too sandy, and partly because insufficient time elapses between tides to permit thorough drying of the sediments.

Ripple marks (see page 170) are parallel ridges on the surfaces of mud or sand produced either by currents or by waves. In most cases they are the results of moving air currents, and are thus, like mud cracks, generally indicative of continental conditions. Oscillatory waves may also disturb the bottom in such a manner as to create one type of ripple marks. Preservation depends upon covering, as in the case of mud impressions or cracks. Most of the ripple marks which have escaped destruction have been formed by water; many such marks are produced by wind action, but are rarely preserved because of lack of covering.

Colors of deposits. The colors of sediments may be due to the influence of the principal mineral present or to that of widely disseminated minor minerals, present as cements, as a coating around grains, or as scattered particles. The chief pigmenting substances are iron compounds and carbonaceous matter, the latter originating in the decay of organic materials. The carbonaceous particles produce dark shades in the sediments in which they are disseminated, ranging from

black or deep blue to dark gray. Ferric (iron) oxide lends a red color to the sediments of which it forms a part, while the common hydroxide of iron produces rusty-brown or yellow colors.

Common Sedimentary Rocks

Conglomerate. A *conglomerate* (page 386) consists of pebbles or gravel embedded in a matrix of finer material, usually of a siliceous composition. A rock of similar character is a *breccia* if the larger components are angular instead of rounded. Although many conglomerates are formed in shallow ocean water, as when the sea is encroaching upon the shore, some of the thickest of such deposits seem to have originated upon the continents, in basins surrounded by mountains.

Sandstone. Most sands consist principally of fragmental quartz grains. Sand may consist, however, of grains of magnetite, gypsum, calcium carbonate, or other common minerals. The consolidation of the incoherent grains into sandstone is brought about chiefly by the deposition between the grains of cementing substances carried there by percolating water. Some cementation may be the result of slight solution and redeposition of silica at points of contact of the sand par-

Isolated mass of almost pure quartz sandstone (St. Peter). Near Oregon, Illinois.

Illinois Geological Survey





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Conglomerate, a sedimentary rock consisting of rounded stones cemented together, often indicates deposition in shallow sea water. The wave-eroded fragments of shore rocks are ground down, rounded, and deposited as basal conglomerate.

ticles; but for the most part it is due to the laying down between the grains of such substances as lime, iron oxide, or silica. Iron oxide imparts its characteristic red, brown, or yellow color to the resulting rock, while lime cement usually produces a white sandstone. A freshly broken surface of sandstone has a gritty feel, produced by the projecting grains of quartz, as fracture takes place in the softer cement.

Arkose is a form of sandstone containing coarse grains of orthoclase. It originates from the incomplete disintegration of such rocks as granite.

Shale. *Shale* is an indurated mud or clay. Mud, like sand, may vary widely in composition, its identity depending upon the size of its constituent grains rather than upon its chemical or mineralogical composition. Most muds are of the argillaceous, or clayey, type, consisting of minute particles of various silicates. True clay contains considerable kaolinite. Nearly pure calcareous (limy) muds exist, although when these have been consolidated they are usually classed as limestone rather than as shales.

The particles which constitute muds and clays are so fine and so closely spaced that there is practically no circulation of water among them. Cementation, therefore, is of very little importance in the consolidation of these rocks, which depends instead largely upon the effects of pressure. Van Hise has pointed out that a gram of dry mud may contain from ten billion to twenty billion particles, as compared with 115,000 to 167,000 grains per gram of fine sand. Thus the number of points of contact of grains of mud or clay particles would be some 60,000 to 174,000 times as great as in the case of sand. Probably for

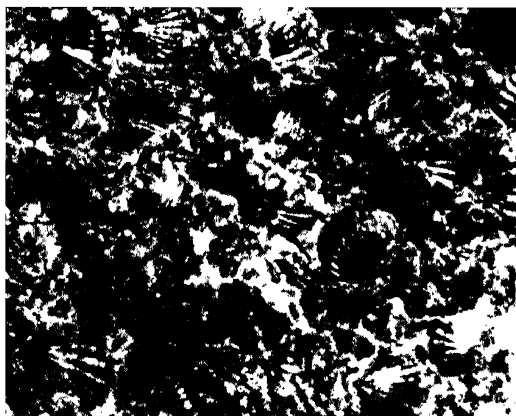
this reason, pressure is a major factor in the consolidation of fine-grained rocks such as shales, but of negligible importance in the induration of sands, since in the former case there are so many more bonds brought within the limits of molecular attraction.

A shale lacks the characteristic gritty feel of sandstone. It is usually soft, friable, and somewhat fissile, due to closely spaced bedding planes. Many shales emit an easily recognized earthy odor when breathed upon.

Limestone. *Limestone*, consisting principally of calcium carbonate, is formed in a number of different ways, some of which are not fully understood. Some limestones are very compact, showing little or no trace of calcareous shells. These rocks may have resulted from the deposition of extremely fine limy powder produced by the attrition of marine shells and bones. In other instances the organic origin of limestones is plainly evident, as in the case of the specimen shown on page 388. Whole beds may consist of fragmentary shells; rocks of such constitution are known as *coquina*. Other forms of limestone, of which chalk may be taken as an example, consist of more or less whole microscopic shells. Much limestone is undoubtedly derived from those associations of lime-secreting organisms commonly known as coral reefs; actually, such reefs contain many organisms other than corals. These plants and animals take calcium carbonate from sea water for use in construction of their shells, which, upon the death of the organism, are left to be added to the growing accumulation. Some of the limestone formed in this way is dissolved and later re-deposited; some is broken up by the waves into calcareous sand; in these and other ways the organic character of the reef becomes blurred, until at length it may be hard to recognize.

Some limestones result from the evaporation of water in which calcium carbonate is dissolved, deposits occurring in lake beds or around the mouths of springs. Fresh-water limestone laid down in the beds of lakes is sometimes called *marl*. A form deposited by springs or rivers, usually of a rather porous texture, is called *travertine*.

Salt and gypsum. Rock salt and gypsum, as well as a few minor rocks of similar nature, are laid down from solution by evaporating waters. Beds of salt are often colored brown or red by iron oxide. Gypsum is likely to appear in massive beds as a white, pink, gray, or



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Some limestones, like the one shown at the left, show clear evidence of their organic origin, containing the remains of corals, stone lilies, shell fish, and other marine forms. Other limestones may show no visible evidences of organic remains. Even these, however, usually originate from the life processes of animals and plants.

dark-colored substance, often resembling limestone, from which it can readily be distinguished by its relative softness and its lack of effervescence when treated with an acid.

Coal. *Coal* may be regarded as another sedimentary rock of organic origin. There is no question that coal has originated from vegetable matter which accumulated under water, thereby escaping normal decay. *Bituminous coal*, or *soft coal*, is usually considered as belonging to the sedimentary class, while *anthracite*, or *hard coal*, is classed as a metamorphic.

Ice. *Ice* (and possibly liquid water) should be classed as a sedimentary rock, and as such it is of considerable geological importance. It originates from the compacting and recrystallization of snow, which has crystallized directly from a vaporous condition (a process known as sublimation) or from the crystallization of water.

THE METAMORPHIC ROCKS

Rocks, in common with the rest of nature, react to attacks of outside forces by assuming conditions of lessened stress. When the changes thus induced become pronounced, they are designated by the term *metamorphism*, although the definition of this expression is attended by considerable ambiguity. Alterations in rocks may begin in magmas before they are fully solid¹; yet alterations may continue for an ex-

¹Rocks so affected (*primary gneisses* or *gneissoid granites*) exhibit a grain or orientation of crystals. This condition is regarded as an instance of incipient metamorphism by some authorities, but not by all.

ceedingly long time, as is indicated by the fact that ancient rocks are on the whole metamorphosed to a far greater extent than relatively young ones.

The chief forces responsible for rock metamorphism are heat, pressure, and chemical reactions. Heat facilitates chemical changes. Pressure acts directly in bringing about internal rearrangements in rocks, and in affecting solubility. Chemical changes are largely the results of the reactions of water and aqueous solutions, and of the gaseous constituents of magmas. According to some authorities even weathering changes (Chapter IV) are to be regarded as metamorphic in character.

Among the more conspicuous ways in which rocks may be altered by these agents of metamorphism, the following should be especially noted: *banding* or *foliation*, *recrystallization*, and the *development of new minerals*. Most metamorphic rocks show evidences of banding (p. 390), or of a platy structure (p. 391), which has resulted from the elongation, flattening, or reorientation of crystals or inclusions, or from the development of new minerals of a platy character. Recrystallization, usually a process of solution or partial fusion followed by deposition in crystalline form, results in a more coarsely crystalline rock. In seeking a state of balanced equilibrium with the environment, many minerals undergo such drastic alteration that their constituent elements are reassembled into different mineral combinations; new minerals also result from the addition of foreign materials brought into the scene by waters or vapors.

The following metamorphic rocks illustrate these common types of change:

Gneiss. While *gneiss* may result from the alteration of rocks of various kinds, it has the general composition of granite, and there is no question that most existing gneisses have originated from rock of this type. Its outstanding characteristic is its coarsely banded structure, its alternating layers of quartz and feldspar being easily recognizable. Biotite and other dark minerals also commonly appear as thin streaks.

Schist. *Schists* often resemble gneisses, but are as a rule more fine-grained and more compactly banded. Feldspar, which is prominent in gneisses, is often absent or nearly so in schists, which are named from their most characteristic minerals, as for example mica-schists, horn-

blende-schists, chlorite-schists, or talc-schists. In most instances crystals are large enough to be visible to the eye. Schists often break along the bands or folia formed by certain minerals, thereby giving the impression that they consist of one mineral only.

Slate. Pressure sufficiently intense to flatten, elongate, and reorient the grains of a rock or to cause the development of new minerals of a platy character may result in the rock known as *slate*. Slates are finer of grain than schists, the individual grains being generally quite indistinguishable, even under moderate magnification. The tendency to split along very smooth, flat surfaces is the chief characteristic of this rock. The color is usually black or dark blue. The great majority of slates are metamorphosed shales or clays, although they may originate from fine-grained igneous rocks.

A *phyllite* is a rock occupying an intermediate position between a slate and a schist. Its grains are coarser than those of the slate, but finer than those of the schist. The surface of a phyllite exhibits a higher luster than that of a slate. Although its crystals are generally indistinguishable to the unaided eye, occasionally large isolated crystals appear.

Marble. When acted upon by heat, pressure, or water, or a combination of these agencies, particles which comprise limestone or dolomite may be recombined into crystals of conspicuous size. The resulting rock is *marble*. This rock is white when pure, but it is often discolored by various impurities. Like limestone, it is soft and effervesces vigorously when treated with an acid.

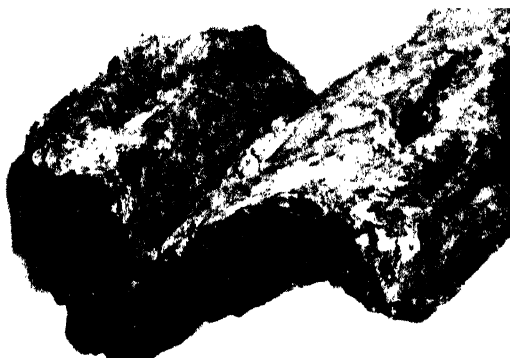
Marble is considered a nonfoliated rock; when pressure has been a sufficiently potent factor in its formation to give it a definite cleavage, it is generally classified as a calcareous schist.

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Biotite gneiss. Gneiss, with its coarsely banded structure, is one of the most common metamorphic rocks. Abundant time, pressure, and heat appear to be factors in the conversion of igneous rocks into gneiss.

Mica schist. A strongly foliated metamorphic rock in which the constituents have been mainly converted into mica. Aided by high pressures and great heat, metamorphism often expresses itself by the formation of new minerals.



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Quartzite. Another nonfoliated rock is *quartzite*, which has resulted from the cementation of quartz sand by silica. As in other metamorphic rocks, all gradations exist between the completely metamorphosed rock and its sedimentary precursor, and many petrologists are inclined to classify quartzite with the sedimentaries; in general, however, a workable distinction between sandstone and quartzite can be made at the point at which silicification has been sufficient to cause the rock in question to break as readily through the quartz grains as through the cement. Because of the absence of projecting quartz grains, the freshly broken surface of a quartzite is smooth in contrast to that of a sandstone.

Thus we see why rocks cannot always be made to conform to hard-and-fast definitions, and why between different kinds there always lie vague and indefinite boundaries. The crust of the earth is a great laboratory, a workshop wherein nature constantly shifts and changes, adjusts and balances, obliterates and reassembles. This conception of constant and universal change is fundamental to a clear comprehension of the processes that are forever remodeling the face of the earth.

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XVII · THE EARTH'S MINERAL WEALTH



The dependence of civilization upon the utilization of the earth's mineral products has become more and more evident with the unfolding of the human story. Stone was man's chief ally in the earliest days of his struggle to secure a foothold on the planet. In historically ancient times rock was quarried for building purposes, and bricks were made from clay. In Babylon and Nineveh masonry was held together by a mortar of pitch, and some streets are said to have had asphalt paving. Men learned to smelt metals from their ores, and the art of Tubal-cain launched humanity upon new adventures.

The coining of money and the finding of other new uses for metals stimulated travel, trade, and exploration. The mineral industry grew amazingly, until at length it attained a position second in importance only to that of agriculture.

Much of the stature of the United States among the nations of the world has been made possible through its possession of abundant supplies of nearly all the vital minerals and fuels. In the past the continued availability of these materials was tacitly accepted as an American birth-right. During the present century, however, both metals and fuels have been consumed at a vastly accelerated rate. Incursions on reserves made by the recent war brought the sobering realization that the country's resources are not inexhaustible, and that some are even now facing virtual depletion.

The rapid consumption of the country's mineral reserves, plus the discovery of new and important uses for minerals not heretofore in demand, opens up new opportunities for geological research in regard both to the locating of deposits and their efficient and economical exploitation. Such work, in fact, is one of the factors which must of necessity be actively pursued if the United States is to continue to maintain its present position in world affairs.

COAL

Coal in the industrial picture. The history of coal reflects the history of modern industry; in it can be read the story of the disappear-

ance of the individual artisan and manufacturer, and the birth and development of the mass production principle, along with vastly improved standards of living. In recent years coal's contribution to civilization has been extended to include much more than its function as the chief industrial fuel. It now yields a great variety of chemical products. Heated in closed retorts, it breaks up into illuminating gas, ammonia, and the ingredients of the aniline oils, the sources of most of our dyes and many perfumes, flavors, and antiseptics. Carbolic acid, aspirin, and other drugs are obtained from the same material, as are creosote, electric insulators, photographic developers, tanning agents, solvents, synthetic fabrics, and many other articles of everyday use.

The ancient Greeks, Romans, and Britons knew of "stones that would burn." The actual mining of coal, however, did not begin in England before the twelfth century, and not until 1760 in America. During the century following 1820 the use of coal in the United States increased nearly a hundredfold. The United States became the leading producer of coal in 1899; at the present time American production accounts for something less than half the world's output, amounting to about 600,000,000 tons annually.

In spite of rapid consumption and of the exceedingly wasteful methods of mining which have prevailed in the past, coal reserves of the United States and other countries remain very great. Estimates place the amount already consumed at less than one half of one per cent of the country's total supply; America still has coal for thousands of years into the future.

The origin of coal. Over a considerable area in Canada, Minnesota, Wisconsin, Michigan, and other northern sections of North America and Europe, one may witness conditions approximating those attending the formation of most of the world's coal deposits. In these localities large swamps, the results of disruption of drainage by continental glaciers, are the sites of assemblages of plants of many different kinds. In Dismal Swamp and the Everglades, and in many a bayou along the lower Mississippi and other southern rivers, water-loving plants grow in profusion. In some of these locations plant tissue is already on the way to conversion into coal.

Dry plant tissue is about one-half carbon, and, if oxidation is sufficiently inhibited, a concentration of this element takes place as a result

of physical and biochemical changes. In a typical peat bog living plants grade downward into plant remains which become less and less recognizable as such, until they may be classed as peat; casual examination of this substance, however, will reveal many plant structures. The water in such a morass is stagnant, preventing access of air. The woody fibers soften, taking on a semigelatinous character. Compression by the weight of the steadily accumulating plant material above squeezes out water and various gases, while the gelatinous substances harden into a cement among the remaining woody fibers. G. H. Ashley has estimated that the accumulation of one foot of compressed peat requires, on the average, about a century of time.

These changes in plant tissue are brought about largely through the action of certain bacteria, which excrete toxins that eventually inhibit their own activity. Even after this point has been reached, however, certain changes may continue. Peat formed in the bog may be buried under sedimentary deposits; volatile matter including methane, carbon dioxide, and carbon monoxide will be given off, thus causing a further concentration of the "fixed" or nonvolatile carbon. In this way the peat is slowly converted into *lignite*, a brown or black material often exhibiting a woody structure. Lignite is light in weight, ignites readily, but yields comparatively little heat.

Further loss of gases and moisture results in bituminous, or "soft," coal. Coal of this class usually has a darker color than lignite, is more compact, and has a tendency to break more or less at right angles to bedding planes. It burns readily with a smoky flame, and has high heating power.

Folding and fracturing promote the metamorphism of coal, chiefly by permitting the escape of water and gaseous hydrocarbons. Deposits of coal which have been severely affected by crustal movements may be altered into anthracite, or "hard" coal. Anthracite has a brilliant luster and fractures along curved rather than plane surfaces. Its percentage of fixed carbon is considerably higher than that of lignite or bituminous coal; it ignites with some difficulty, and burns with high heat and little flame. Under certain conditions anthracite may suffer further metamorphism, crystallizing into *graphite*.

The effects of crustal disturbances on the metamorphism of coal are plainly illustrated by the coal deposits of the United States. The large deposits of North Dakota and northeastern Montana are almost en-

tirely of lignite of very low grade. The quality of the coal improves southwestward, becoming high near the mountains. This is shown also in the coals of Ohio and Pennsylvania, which have been affected by deformative movements which increase toward the east; in this case the proportion of fixed carbon increases from west to east, culminating in the anthracite field of eastern Pennsylvania.

Time is another factor in the changes affecting the quality of coals. In general, the older deposits contain the best coals.

Occurrence of coal. Coal beds underlie approximately 330,000 square miles of the area of the United States. Deposits in China are almost as extensive, and include much anthracite. Russia has substantial deposits of coal, as have Australia, Great Britain, and France.

The great bulk of the coal mined in the United States comes from the eastern half of the country. Pennsylvania produces about one half of the country's total, and practically all of its anthracite. The most important coal fields of the United States are the following:

1. The Appalachian field, extending from Pennsylvania to Alabama, a distance of about 900 miles, and varying in width from 30 to 180 miles. In area this field covers some 70,000 square miles, of which the anthracite-producing portion in eastern Pennsylvania comprises but 500 square miles. This is the most important producing field in the United States.

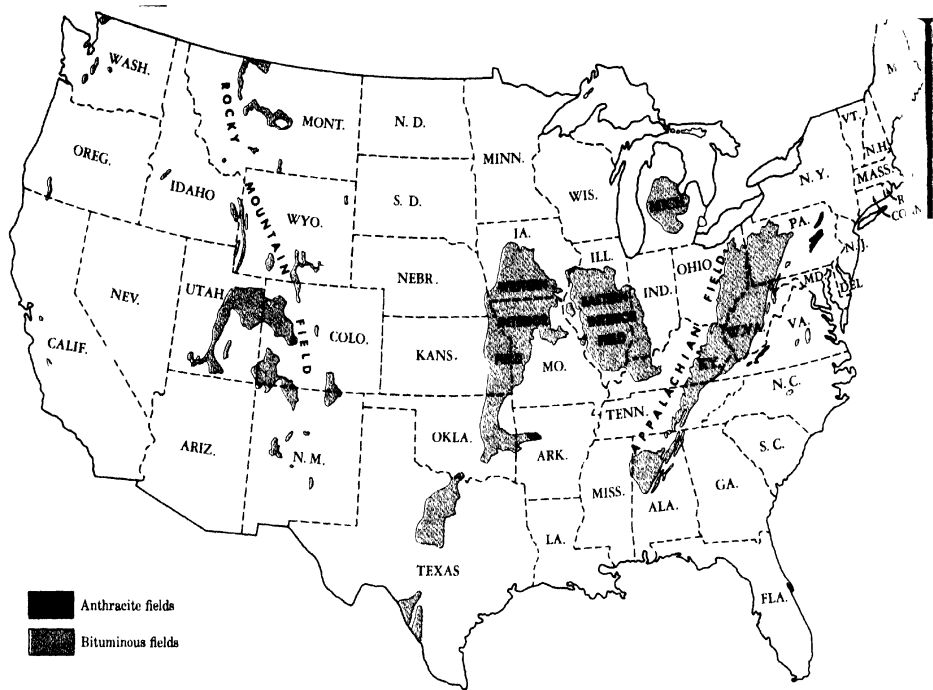
2. The Michigan field, embracing a section of 11,000 square miles in southern Michigan.

3. The eastern interior field, located principally within the state of Illinois.

4. The western interior field, extending from Iowa through eastern Kansas and Oklahoma into Texas. The area of this field is about 75,000 square miles.

5. The Rocky Mountain field, comprising scattered areas in the northern Great Plains and Rocky Mountain sections. The coal beds of this field underlie approximately 125,000 square miles. Coals are of various grades, but are little worked. Colorado is the principal producing state of the area.

6. The Pacific coast fields, which consist of scattered groups of deposits in the Pacific states. The coal is of poor quality, and is not extensively mined.



Map showing the distribution of coal fields in the United States.

7. The Gulf coast field, chiefly in southern Texas. The coal of this district is mostly lignite, and is of little commercial importance.

The world's total reserve of coal has been estimated at 7,400,000,000,000 tons, of which 5,000,000,000,000 are in America. Over half of the American supply, however, is lignite or subbituminous coal. Asia has deposits which have been placed at 1,280,000,000,000 tons, including 400,000,000,000 tons of anthracite. European deposits are estimated at about 780,000,000,000 tons.

PETROLEUM AND NATURAL GAS

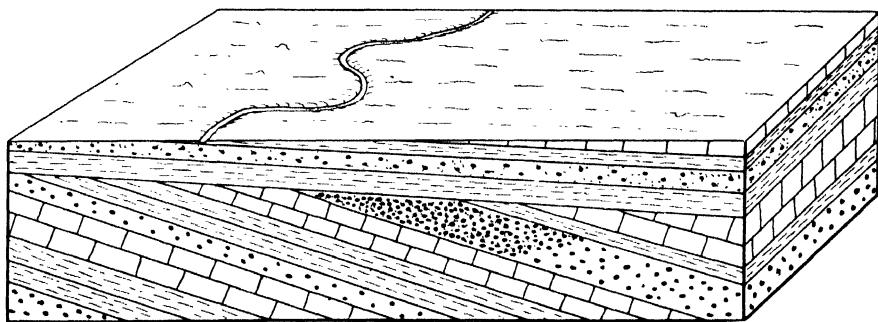
The nature and uses of petroleum. Petroleum is a mixture of substances known as hydrocarbons. These compounds consist chiefly of the elements hydrogen and carbon, although in many cases small amounts of sulfur, oxygen, nitrogen, or carbon dioxide may be present. Hydrocarbons form a series, occurring as gases, liquids, and solids; those with the fewest carbon atoms comprise natural gas, those with a larger number crude oil or petroleum, and those with many carbon

atoms asphalt or paraffin. Natural gas and petroleum usually occur together, although there are exceptions. Asphalt deposits or "tar pools" are commonly regarded as old petroleum reservoirs from which the more volatile gaseous components have escaped.

The chemical composition of petroleum varies notably from well to well, and even from the different sands encountered in the same well. With change in composition there occur variations in such physical properties as odor, color, density, solidification point, and boiling point. The value of a crude oil depends very largely upon its density. This may range from 0.7 to almost 1.0. Oils of lower density are nearly always lighter in color, have a lower boiling point, and yield a greater gasoline content.

When petroleum was first discovered, its chief claim to importance was as a source of kerosene. Later it came to be refined principally for its gasoline and lubricating-oil content. Today the additional demand for fuel oil and for certain higher derivatives such as butadiene have made petroleum the most valuable of all mineral substances. Exploration for new sources of oil is being carried on more intensively than ever before, despite the fact that production is greater than at any previous time in history.

Occurrence and origin. Nearly all petroleum and natural gas are found in sedimentary rocks. Sandstone is the most common reservoir rock; therefore the term oil sand is generally applied to the oil-bearing formation, whether this consists of sandstone, limestone, shale, or conglomerate. The producing horizon may be a sand only a foot or two in thickness, or, as in California, it may be a petroliferous zone 2000

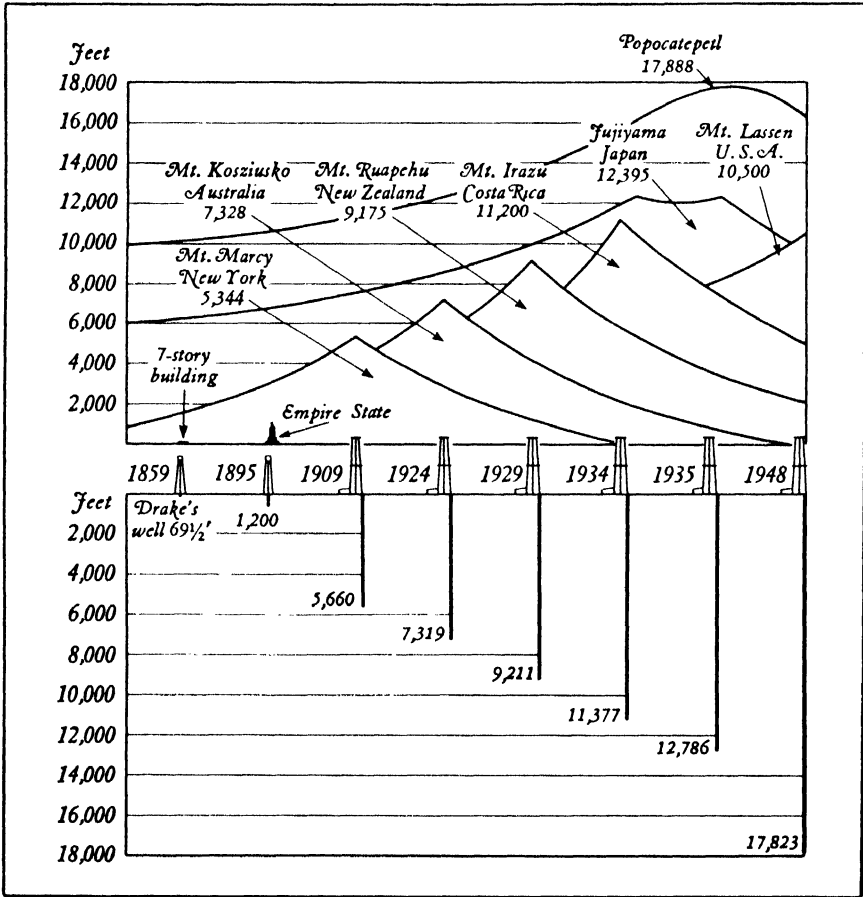


A stratigraphic trap.

to 3000 feet thick. Several different oil and gas sands may be encountered in the same well. Fortunately, the deeper sands, which are naturally the most expensive to exploit, usually contain the higher grades of petroleum.

In the early days of the oil industry, wells were generally drilled to a depth of from fifty to one hundred and fifty feet. Wells of more than 10,000 feet are now fairly common, and the deepest are in excess of 20,000 feet. The chart below shows how the depth of oil wells compares in footage with the height of mountains.

The energy which brings oil to the well from the surrounding rock is supplied either by natural gas associated with the oil in the sand, or



Committee on Oil Information

The drill penetrates ever deeper into the earth in the continuing search for oil.

Right, an oil sand; left, a "dry" sand. An oil sand is generally discolored and may have a distinct petroleum odor. Petroleum deposits may occur in almost any kind of porous rock, the oil occupying the spaces between the grains.



Standard Oil Co. (N.J.); photograph by Loftman

by the force of water under hydrostatic pressure. As the reservoir energy declines, production of oil decreases. Secondary methods of recovery are sometimes employed in the later life of a pool. These consist primarily of restoring some of the reservoir energy by introducing gas or water into the sand at carefully selected points.

Probably less than half of the oil wells of the world flow their oil to the surface naturally. Pumping must be resorted to in the later stages of most wells, and in the primary stages of many wells. Only one well in the United States ever produced as much as 100,000 barrels of oil within the space of twenty-four hours, but a well near Tampico, Mexico, is estimated to have produced fully twice that amount. Several wells have produced more than a million barrels of oil in their lifetime, but such production is most unusual.

Petroleum and natural gas are now generally considered to have been of organic origin. The animal and vegetable material from which they were derived are believed to have been deposited in salt-water or brackish-water basins, where they underwent a series of changes involving bacterial action, burial, heat, pressure, and chemical alteration. Sufficient deformation of the containing rocks might result in complete distillation of the more volatile hydrocarbons, leaving only a solid asphaltic residue.

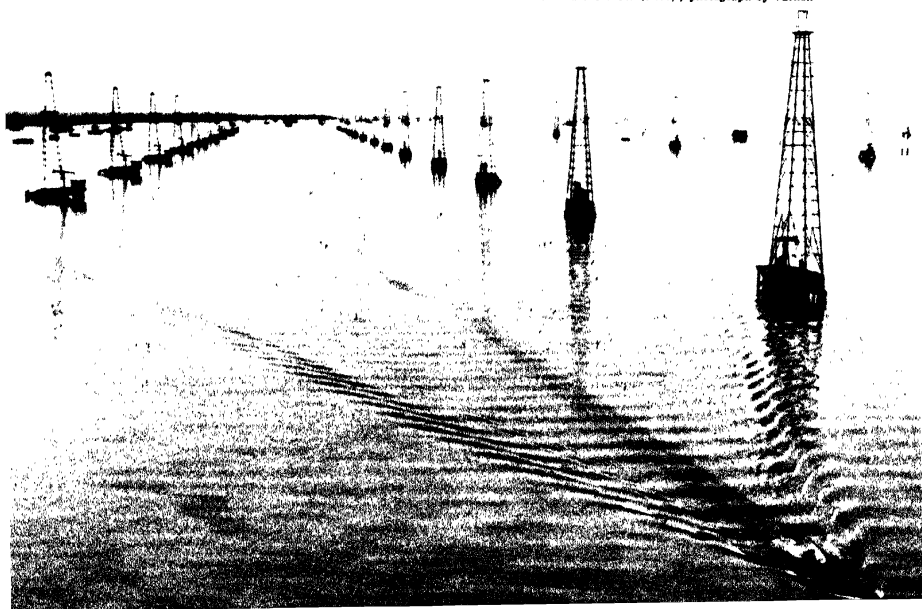
Whenever oil, gas, and water, or any two of these substances, occur together, they will tend to arrange themselves with reference to their respective densities, with the gas above and the water on the bottom. In a section of alternating porous and impermeable rocks oil and gas would be trapped at places where the rocks have been folded into the form of anticlines or domes, or where a layer of porous rock terminates abruptly against a fault, intrusion, or unconformity. These relationships are shown in the diagram on page 397. In the search for accumu-

lations of petroleum and natural gas much attention is given to locating these structures. Not all oil and gas occur in this type of trap, and certainly many such apparently favorable structures contain neither. Much attention has been focused in recent years upon the structure known as a stratigraphic trap, an example of which is illustrated on page 397. The great eastern Texas oil field, which may eventually yield a total recovery in excess of five billion barrels of oil, produces from a structure of this kind, in which the oil is trapped in the upper ends of permeable strata beneath an angular unconformity. Nevertheless, the dome and the anticline are recognized as the most favorable sites for accumulation. Structures are hunted, not only by geologists who map rocks which outcrop, but also by those who make surveys of deeply buried folds with the aid of geophysical instruments. The most successful of these instruments has been an adaptation of the seismograph, which reveals the structure of the rocks beneath the surface by recording the rate at which waves from artificially induced tremors are reflected and refracted by the buried layers. By such means it has been possible to extend the search for oil over the continental shelf of the coasts of Louisiana, Texas, and California.

Petroleum and natural gas are widely distributed, both stratigraphically and geographically. They have been found in commercial quantities in all but the very oldest of rocks. Asia, Europe, South America,

Into lake and sea goes the search for oil. Laguilles field, western Venezuela.

Standard Oil Co. (N.J.), photograph by Yachon





*Mining asphalt from the famous "asphalt lake" on the island of Trinidad,
British West Indies*

and North America all have important deposits. The United States up to the present time has produced nearly 70 per cent of all the oil produced by the world; this rate, however, cannot be maintained, for more than half of the world's reserves of petroleum are located outside the United States. Mexico, Venezuela, Colombia, Argentina, and Peru are all important oil-producing countries. The greatest reserves now known are located in the area east of the Mediterranean Sea in the countries bordering the Persian Gulf. Within the United States the states which lead in oil and gas production are Texas, California, Louisiana, Oklahoma, and Kansas. Twenty-three states have commercial production, although in several cases it can be considered negligible.

Natural gas. Natural gas consists principally of methane (CH_4); but many other hydrocarbons may be present. Of these ethane (C_2H_6) is important because it adds greatly to the heating value of the gas. Natural gas is generally considered to be colorless and odorless. It is highly explosive when thoroughly mixed with air. Noninflammable

impurities are often present, sometimes in such quantities as to make up the entire volume of gas in a well. Nitrogen and carbon dioxide have each been found in quantities exceeding 90 per cent of the gas in individual wells. Helium, though very uncommon, may constitute nearly two per cent of the volume of wells in which it occurs. Sulfurous gases are more common, hydrogen sulfide being of most frequent occurrence. Although natural gas containing large quantities of these substances has little or no heating value, such impurities as helium and carbon dioxide may be commercially recoverable.

Although natural gas is usually associated with petroleum, some of the largest gas pools in the world, such as the Hugoton Pool of southwestern Kansas, have little or no oil in the gas sand itself or in the lower formations which have been tested.

The viscous to solid material called asphalt, which is widely used in some types of paving, is in part obtained as a by-product of the refining of petroleum. There are, however, natural deposits of asphaltic material in many parts of the world. Trinidad Lake, on the island

A mountain of oil shale near Rifle, western Colorado (see map, p. 404). Such deposits as this may constitute a major source of oil for future generations.

United States Bureau of Mines



of Trinidad, off the northern coast of South America, is the best-known example. The Athabasca Tar Sands of Northern Alberta is another. Still others occur in many of the oil-producing states.

Oil Shales. Much attention has been given in recent years to the possibility of obtaining oil products from the rock known as oil shale. Known for years in Scotland, where this rock has served as a source of both oil and ammonia, it aroused interest in this country when the possibility of exhaustion of petroleum supplies from the regular sources began to emerge. "Oil shale" is not always a shale; in many cases it is a shaly limestone or dolomite. It does not contain oil, but a carbonaceous material known as kerogen, which yields hydrocarbons upon distillation. The organic material present consists largely of microscopic particles of vegetation, such as spore cases and the remains of algae, together with occasional stems and leaves and some animal matter.

Oil shales are widely distributed throughout the world, and are encountered in many parts of the United States. The richest deposit in this country is the Green River formation, occurring in Wyoming, Colorado, and Utah (pp. 402 and 404). This formation, more of a marl than a true shale, was laid down in lake waters occupying intermontane basins. Its potentialities for oil production are enormous, exceeding by several times those of known natural deposits. The United States Bureau of Mines has constructed a pilot plant near Rifle, Colorado, for the purpose of pointing the way to commercial production from this and perhaps other similar formations.

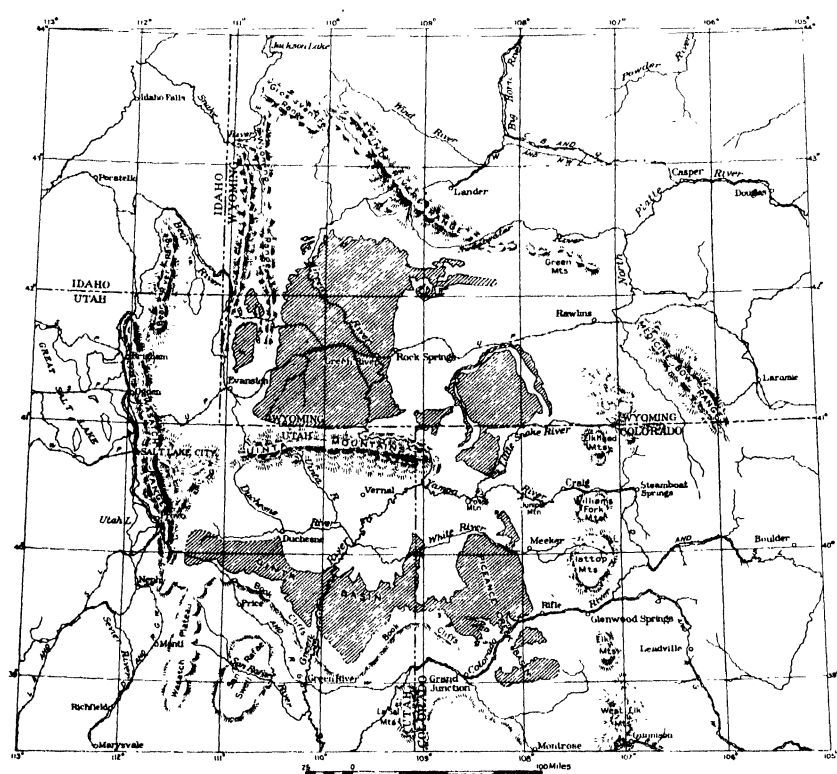
Tar sands. Another possible future source of petroleum which should be mentioned if only because of the great size of its deposits is to be found in masses of asphaltlike material known as tar sands. These are widely distributed, but by far the largest deposit is near the Athabaska River north of Edmonton, Alberta, Canada. Recovery of oil from these sands is a technically difficult process.

It appears quite possible that the coal deposits of the world will be called upon to serve as a source of hydrocarbon products long before either oil shales or tar sands are utilized on any very extensive scale. In the Second World War Germany was very successful in manufacturing gasoline through the process of hydrogenation of coal. This method is reported to be cheaper than the refining of oil shales; and

there is an abundant supply of coal in the United States and elsewhere available for this purpose. Natural gas can also be counted upon to supply large quantities of gasoline.

THE METALS

Ore deposits. The term *ore* is defined as a deposit of metallic minerals sufficiently rich to permit its profitable exploitation under the existing conditions. Whether any deposit or portion of a deposit is to be considered as an ore body is determined by such factors as the concentration of the mineral in the rock, transportation facilities, cost and availability of labor, cost of mining machinery, and current price of the metal. A comparatively lean deposit may constitute ore while



United States Bureau of Mines

Locations of the Green River oil shale formation of Colorado, Utah, and Wyoming. This formation is estimated to contain the equivalent of more than 300 billion barrels of oil, many times the known reserves of natural petroleum.

a much richer one cannot be so considered, and the same deposit may meet the terms of the definition at one time, and fail to do so at another. During the First World War the high cost of labor and materials forced the closing of numerous gold mines, since gold, having then a fixed value of \$20.66 an ounce, could not in many cases be mined at a profit. The present enhanced value of gold reverses these conditions, and gold is being profitably extracted from veins and gravel beds the yields of which are much too meager to have made their exploitation worth while before.

The original source of the metals is the igneous rocks, in which they are ordinarily widely disseminated. They appear in many cases to have issued from stocks or batholiths in the form of vapors, to be deposited in the country rock surrounding the intrusion. In a few instances the metals are present in native or elemental form. Thus gold, silver, platinum, copper, mercury, and a few other metals occur uncombined. The great majority of ores, however, contain the metals in combined form, as sulfides, oxides, or other compounds. Associated with the metallic minerals there usually occurs a quantity of worthless earthy material constituting *gangue* minerals. The most common gangue minerals are quartz, calcite, barite, fluorite, and siderite, though many others may be present.

Some ore deposits are of the same age as the rocks in which they occur. This class includes a small number of bodies of ore which separated directly from solidifying magmas. Another example is to be found in certain deposits interstratified with layers of sedimentary rocks, such as some iron ores which have been deposited through sedimentary processes. A common member of the latter group is the *placer* deposit, which consists of an accumulation of heavy metallic minerals such as gold, platinum, or tin in stream or marine gravels or sands.

Much more abundant are ores which have been derived from magmas and which have found lodging through the invasion of older rocks. Steam given off by crystallizing magmas forces its way under high pressure into pores and fissures of the country rock. With it are carried metallic emanations of the parent magma, as well as certain other substances, some of which may promote the solubility of the metals. The ore materials are carried upward and outward until reduced temperatures and pressures, or contact with chemical substances

which reduce solubility, result in their deposition in the surrounding rocks. Deposition may consist of *cavity filling* or of *replacement*, which involves the removal by solution of parts of the invaded rock and the simultaneous deposition of the introduced mineral matter in the place of that removed.

The principal types of ore deposits may be summarized as follows:

1. Ore bodies may be formed through the gravitational separation of the materials of a magma, a process known as *magmatic segregation*. This process can be most easily recognized in such structures as laccoliths, since these have definite floors upon which the heavier constituents of the magma can settle. Compounds of iron, nickel, titanium, and other metals have been concentrated in this manner.

2. Deposits resulting from *contact metamorphism* occur chiefly in sedimentary rocks, especially limestones. Such ore bodies are either in contact with an intrusive mass from which the metals have escaped, or very near such a mass, usually within a few hundred feet or yards. The invaded sedimentaries are metamorphosed by replacement through the agency of hot vapors issuing from the igneous mass. A deposit of this kind may be of very irregular shape and contain ores of copper, iron, zinc, and sometimes gold, silver, lead, and other metals.

3. The most common type of ore occurrence is that in which metals are deposited in *veins*. A vein is a fissure which has been filled with mineral matter as a result of cooling, reduction of pressure, evaporation, or change in the chemical nature of the depositing solution. Veins are exceedingly variable in size, shape, and structure. They may be simple and regular, with distinct parallel walls, or they may be multiple and of irregular structure, with walls that swell in places or pinch out in others. Frequently the walls of a vein are found to have been invaded by the mineral-bearing solutions and partly replaced, so that the boundaries of the deposit are indefinite.

Several closely spaced veins constitute a *lode*. The country rock separating the individual veins of a lode is often to a considerable extent replaced by metalliferous material, converting the entire structure into an ore body.

Veins are usually found to have had their origin in larger intrusive masses, such as stocks or batholiths. In some cases veins extend downward into the parent structures as much as several thousand feet, in-

dicating that the upper portions of the latter had solidified before they were invaded by vein-forming solutions from the still-molten interior.

A large number of valuable minerals occur in veins, among them gold, silver, copper, tin, nickel, lead, zinc, iron, mercury, and manganese. Often more than one metal is recovered from the same vein.

4. *Sedimentary ore deposits*, exemplified by many iron deposits and by placers, have already been touched upon.

Weathering and enrichment of ore bodies. Some of the earth's most valuable deposits of metals have undergone much concentration by the weathering and removal of some of the associated gangue minerals. Thus the removal of silica from aluminum-bearing rock at Bauxite, Arkansas, has resulted in an extremely rich aluminum deposit. The percentage of iron in the great deposits of the Lake Superior region has in places been more than doubled by similar processes.

Ore deposits of nonsedimentary origin also undergo weathering changes that commonly result in enrichment. In the portion of an ore body exposed at the surface, sulfides are oxidized, their products generally combining with water and carbon dioxide with the forma-

Newer methods of extraction promise to enable the mighty Mesabi Range to continue its prodigious output of iron ore for many years to come.

Minnesota Tourist Bureau



tion of new minerals. Pyrite, which is almost always present, oxidizes to sulfuric acid and ferrous sulfate. The sulfuric acid dissolves copper, silver, zinc, and other substances, which are carried downward in solution. The ferrous sulfate is further oxidized to iron hydroxide which, being insoluble, remains at the surface, imparting a conspicuous rusty color to the outcrop.

Since oxidation is limited to the region above the water table, certain metals are brought down to and concentrated at or below this level. An outcropping ore body, originally containing the sulfides of various metals, may come to contain insoluble components such as iron hydroxide and gold at the surface, but very little copper or silver; the latter may be concentrated near the water table, while beneath it lies a zone of sulfides in their original unaltered condition.

Iron deposits. Iron, the fourth most abundant element in the earth's crust, occurs in more than one hundred minerals. Only four or five of these, however, are sufficiently plentiful and rich in iron to serve as ores. The most important iron-bearing minerals are the following:

Mineral	Composition	Percentage of Iron	Mineral	Composition	Percentage of Iron
Hematite	Fe_2O_3	70	Magnetite	Fe_3O_4	72
Göthite	$\text{FeO}(\text{OH})$	63	Siderite	FeCO_3	48.27

The iron minerals are always associated with more or less gangue, so that the percentage of the metal in workable deposits is generally much less than those given above; most commercial deposits run from 30 to 65 per cent iron.

Hematite is by far the greatest source of iron in the United States, accounting for about 90 per cent of the nation's output. Magnetite and göthite are responsible for the remainder. Siderite is the chief source of production in Great Britain, but as an ore is of practically no importance in the United States. Iron is rarely obtained from pyrite, and then only as a by-product of the extraction of sulfur.

In the United States, Minnesota produces considerably more iron than all other states combined; it is followed by Michigan and Alabama. The world's greatest deposit of the metal thus far exploited lies northwest and south of Lake Superior. A view of the famous

Mesabi Range of Minnesota is shown on page 407. Another important deposit is that containing the "Clinton ore," which extends from New York to central Alabama; this ore is mined near Birmingham. The largest deposits of magnetite occur in northern Sweden. Deposits of a commercial or potentially commercial character also occur in northern New York, in New Jersey, in Pennsylvania, and in a few other states. Vast deposits in Labrador, possibly exceeding in size those of Minnesota, are now being actively investigated, and give promise of yielding a great deal of iron in the near future.

The consumption of iron in the United States increased some twenty times while the population of the country doubled. It is a matter of grave concern that ores of the highest grade are being rapidly exhausted. It is evident that continued use of iron at the present rate must depend largely upon the efficiency with which the remaining enormous reserves of lower-grade ores are handled; fortunately, the recent application of new methods of recovery gives every prospect of solving this problem.

Copper deposits. Copper occurs as

Native copper, Cu	Chalcocite, Cu_2S
Chalcopyrite, CuFeS_2	Cuprite, Cu_2O
Bornite, Cu_5FeS_4	Malachite, $\text{Cu}_2(\text{OH})_2\text{CO}_3$
Azurite, $2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$	

and in quite a number of other minerals. Next to iron, it is the most useful metal of modern times. It was the first metal used by man, and as an ingredient of bronze it played an extremely important part in the development of the human race. It is still alloyed with tin to form bronze, which is harder than either of its constituents, and with zinc to make brass. It finds its chief usefulness, however, in the electrical industry, because of its high electrical conductivity.

Existing copper deposits are largely the results of activity of magmatic waters. Together with silver, gold, and some other minerals, it is commonly found in veins associated with intrusions, in contact metamorphic deposits, or disseminated through the country rock. Most of the deposits now worked do not contain more than 2 per cent copper.

From one fourth to one half of the world's copper is produced in the United States. Chile ranks second, followed by Canada, Rhodesia,

Belgian Congo, Russia, and Japan. The principal copper-producing states are Arizona, Utah, and Montana. Nevada, Michigan, and New Mexico also produce notable amounts.

Lead and zinc deposits. The principal ores of these metals are the sulfides galena, PbS , and sphalerite, ZnS . The two are commonly associated, and may be accompanied by copper, silver, or gold. Veins which carry lead ores near the surface may grade into zinc-bearing deposits at greater depth; this is because of the greater rapidity with which the zinc minerals are weathered and removed.

The ores of these important metals occur in veins and cavities, as contact metamorphic deposits and as disseminated masses or irregular bodies in limestone. The country's most important lead-and-zinc field is the Joplin district of southwestern Missouri, southeastern Kansas, and northeastern Oklahoma. These metals are mined in many other states, especially those of the Rocky Mountain district.

Gold and silver. Gold occurs native or as gold telluride. In either form it is usually associated with pyrite and other metallic minerals. Silver is also found native, and in the form of a number of sulfides, of which argentite, Ag_2S , is the most abundant. It is commonly associated with gold, pyrite, copper minerals, galena, and sphalerite.

Veins and similar filled cavities yield the major part of the country's gold and silver. Placer deposits were formerly the chief sources of gold, as well as of small quantities of silver. In these gravels gold occurs as nuggets, grains, or dust. Particles are generally very fine; Lindgren states that particles worth one two-thousandth of a cent are large enough to be visible. In the recovery of the metal from placers, panning, hydraulic mining, and dredging are employed.

South Africa, Canada, Russia, and the United States are the leading gold-producing countries at the present time. Mexico leads in the production of silver, followed by the United States.

Other metals. Aluminum, at one time a rare and costly metal, is now recovered cheaply and in abundance through electrolysis of an oxide of aluminum obtained from bauxite, a mixture of aluminum hydroxides. Bauxite is the result of the weathering of aluminiferous rocks. Nearly the whole of the domestic output of the United States has come from Arkansas; deposits also occur in Tennessee, Georgia,

and Alabama. Germany, France, Canada, and Russia also produce much aluminum.

Bauxite ores of high grade are now practically exhausted. However, a newly developed process makes possible the extraction of aluminum from certain ordinary clays. Clays of the necessary type are widespread, but the operation of the process is still somewhat expensive.

Nickel and cobalt are two important metals which are usually associated in their ores, which include a large number of different minerals. The largest production is from Canada. Negligible amounts of nickel are produced in the United States.

Tin is obtained chiefly from cassiterite, SnO_2 , a hard, heavy, brittle mineral occurring in veins and placers, the latter being the chief source of the metal at the present time. The world's supply comes largely from the Malay Peninsula and from Bolivia; a few localities of the United States, including the Black Hills (South Dakota and Wyoming) and North and South Carolina, give some promise of possible future production.

Mercury, useful in the manufacture of drugs, explosive caps, and scientific instruments, appears to have found a new use in the invention of a new type of electric cell. It is mined in the form of cinnabar, HgS , and as native mercury. California and several other western states produce it in some quantity.

Mention should be made of promising progress which is being made in the extraction of metals, notably magnesium, from sea water. Like several other metals once regarded as too rare for ordinary uses, magnesium, because of its strength and lightness, and the abundance in which it is now being produced, is finding a place in the making of many implements heretofore usually constructed of steel.

THE NONMETALS

Building stones. Nearly every kind of rock can be utilized in some way in construction. The requirements of a building stone are various, depending upon the use for which it is intended. Generally speaking, such a stone should be hard and firm, of low porosity, resistant to weathering, of good color and general appearance, and much stronger than necessary to meet all demands likely to be made upon it.

In the building trade the term *granite* is used to include a wide

range of crystalline igneous and metamorphic rocks. Most of these rocks resemble true granite in having great strength and durability, and are in many cases of handsome appearance. Granite is quarried in Maine, Vermont, and several other states of the Appalachian belt. It occurs also in abundant quantity in Wisconsin, Minnesota, and northern Michigan, and in small amounts in Missouri, southern Oklahoma, and central Texas. It outcrops over great areas in the Rocky Mountains and in the Pacific coast states.

Limestones, dolomites, and marbles constitute an extremely important source of building and ornamental stones. These rocks are comparatively easy to work, and frequently present a very pleasing appearance. Outcrops occur chiefly in the interior states, between the Rocky and the Appalachian Mountains. Limestone is mined extensively near Bedford, Indiana, in Minnesota, and in Missouri. Vermont is the principal marble-producing state.

Sandstone is quarried in Massachusetts, Connecticut, New York, Ohio, and elsewhere. It was formerly of much greater importance as a building stone than at the present time. The adaptability of sandstone to construction work depends very largely upon how well its grains are cemented; many sandstones, because of poor cementation, are practically worthless.

Slates provide a valuable roofing material. They are quarried in the Atlantic states and in California, Minnesota, and Arkansas.

Clay, sand, and gravel. The usefulness of clays stems largely from their plasticity when wet, and their rigidity and hardness when dried and heated. For certain purposes, the amount of shrinkage upon drying or burning and the degree of temperature required to produce softening are also important properties.

The chief use of clay is in the making of brick. Clays suitable for this purpose are very widespread; there is probably no state in which brick pits are not operated.

The manufacture of the better grades of pottery, such as chinaware and porcelain, demands a pure, fine-grained white clay. Clays of this type are found in Georgia and South Carolina.

Fire clay is a clay capable of withstanding high temperatures. It owes its refractory properties to the fact that it contains but small quantities of such elements as calcium, sodium, magnesium, and iron,

which act as fluxes, combining with other ingredients of the clay to form compounds of low melting point. Beds of fire clay often underlie coal seams. Ohio, Missouri, Pennsylvania, and a number of other states have deposits of fire clay.

Bentonite is a clay resulting from the weathering of volcanic ash. It has found an important use as a rotary drilling mud. Wyoming and South Dakota produce most of the domestic supply.

Fuller's earth is an absorbent clay used for the decolorizing of fats, oils, and greases. Deposits of considerable size occur in Georgia, Florida, and Texas; Illinois also has some production.

Siliceous sand has many uses, such as in the making of cement, glass, and the molds for castings. Sand and gravel are employed extensively for road coverings. These materials have a very wide distribution.

Lime and cement. When limestone is heated to about 1100° F. it breaks up into carbon dioxide and calcium oxide (quicklime). The addition of water to the latter compound produces slaked or hydrated lime. Limestone containing quantities of clay and silica is upon heating converted into cement, the "impurities" combining with the lime to form compounds which do not slake upon the addition of water, but crystallize, or set. One of the principal of the many uses of lime is in the making of mortar, which is a mixture of lime and sand. Cement binds together sand grains and gravel or pebbles, forming concrete.

Salt and gypsum. Common salt, sodium chloride, occurs in ocean and lake waters as beds of rock salt interlayered with sediments, in ground waters, and in brine springs. Of much the greatest importance, commercially, are the rock-salt deposits, the origin of which is still somewhat obscure. From these beds salt is recovered either by ordinary mining methods or by forcing water into the salt-bearing formations through holes drilled for that purpose and pumping out the resulting artificial brine. Salt also occurs in the Gulf coast region in the form of huge *domes*, masses of salt below the surface which may be more than a mile in diameter and 1000 or 1500 feet thick. These structures have been but little exploited.

Salt is frequently associated with gypsum, less commonly with lime-

stone. The immense salt deposits of central Germany contain much potash, valuable as a fertilizer. Potash is also present in important quantities in eastern New Mexico and western Texas, part of a very extensive deposit of salt and gypsum extending across western Oklahoma and Kansas. Salt, gypsum, and what is probably the world's largest deposit of potash occur west of the Ural Mountains in Russia. In the United States salt is mined chiefly in Ohio, Michigan, New York, and Louisiana. On a small scale it is recovered by the evaporation of the waters of San Francisco Bay and Great Salt Lake.

Gypsum, hydrous calcium sulfate, is also mined in many countries. New York and Michigan are the leading producers of the United States. Gypsum finds many diverse uses, as in the manufacture of Portland cement, plaster, wallboard, plaster of Paris, and stucco; as a fertilizer; and as an ingredient of paint.

Fertilizers. The growth of plants requires the presence in the soil of a considerable number of different elements, of which only three—nitrogen, potassium, and phosphorus—are likely in the average situation to be seriously deficient. Nitrogen shortage can be overcome to some extent by the growing of leguminous plants, which harbor in their roots bacteria which have the capacity to capture atmospheric nitrogen and fix it in the soil. Most soils, however, require the application of nitrates in the form of commercial fertilizers.

Nitrates are extremely soluble, and their occurrence in quantity is hence restricted to desert regions or other localities in which they are but little subjected to the action of water. Many deposits are known in the western parts of the United States, but these are of small size or poor grade; almost all the nitrates used in this country are imported from Chile, where they occur in the desert region between the Coast Range and the Andes.

Potassium salts are imported from the Stassfurt region of Germany. The deposit in New Mexico and western Texas offers some promise of future production.

Sedimentary beds containing variable quantities of calcium phosphate and calcium carbonate (phosphate rock) are the important sources of phosphorus for agricultural purposes. Beds of this kind occur in the United States, chiefly in Florida and Tennessee, and in North Africa and Russia.

DURATION OF THE COUNTRY'S MINERAL RESOURCES

An unpublished report by the United States Geological Survey and the Bureau of Mines in 1947 gives the following estimates of the probable duration of the country's mineral resources, based upon known deposits, present rate of consumption, and present methods of recovery. It should be noted that now unknown deposits of some of these materials undoubtedly await discovery, and that new methods of exploitation will in some cases extend the workable life of certain deposits far beyond the indicated term; immediate prospects for the utilization of low-grade iron and aluminum ores appear especially encouraging.

Product	Estimated Life from 1947	Product	Estimated Life from 1947
Coal, bituminous and lignite	4000 years	Iron	76 years
Coal, anthracite	187 years	Aluminum	23 years
Salt	Supply unlimited	Arsenic	50 years
Nitrates	Supply unlimited	Bismuth	36 years
Phosphate rock	600 years	Zinc	20 years
Potash	100 years	Gold	19 years
Sulfur	36 years	Copper	19 years
Fluorite	33 years	Silver	13 years
Petroleum	15 years	Cadmium	11 years
Natural gas	55 years	Lead	10 years
		Vanadium	8 years

XVIII · GEOLOGY, THE SERVANT AND ALLY OF MAN



It is doubtful whether any other science has been so closely related to the activities and welfare of man as the science of geology. Long before civilized man began his tenure on the earth, the savage tribes depended upon rocks and minerals for their weapons, their crude tools, and even for material for the decoration of their bodies. Natural caves were their first dwelling places and the springs and streams their water supply. The lakes and streams furnished not only food and water but highways for travel. The mountain chains often formed barriers which effectively determined the territory of separate groups of people. The role which physiography played in the development of the United States has been emphasized by all writers on the history of this country.

Civilized man found thousands of uses for all the materials of the earth. Fuels, metals, medicines, fertilizers, abrasives, structural materials, and countless other substances that affect the daily existence of everyone are the contributions of geology. Some of the minerals of economic importance have been discussed in an earlier chapter. Many phases of geology other than that encompassed by the use of minerals should be emphasized.

The water supply for domestic and industrial uses comes from lakes, rivers, springs, or wells. The suitability of each source is determined largely by geologic factors. Hydrology, which is one of the more important divisions of geology, has been of very great importance to communities or individuals that are seeking information regarding the behavior of their water wells or the location of new sources of supply.

In the Great Plains area of the western United States the geologist has been responsible for determining the location of many artesian wells, some of which, in Colorado and Oklahoma, are used for irrigating land. Others furnish the water supply for smaller cities and for industry.

Increasing attention is being given to the matter of soil conservation.

Here again geology plays a most important role. The soil itself is principally the result of disintegrated and decomposed rocks, with which a smaller amount of organic material is mixed. The physical characters of soil are therefore largely determined by the source rock from which it comes and the geologic processes by which it is formed. A sandstone rock changes into soil largely by disintegration and therefore forms a sandy quartz soil which is often lacking in most minerals important to plant growth. Similarly, shale rock forms a clayey soil. Calcareous rocks like limestone and dolomite are weathered principally by solution. The part of the rock which is left behind to form soil is the clayey impurities which are always present in greater or less amounts. Consequently the soil formed from limestone may have practically all of its calcium carbonate leached out and actually be deficient in lime.

Part of the soil-conservation program is concerned with preventing too rapid a runoff of water which falls as rain. This is accomplished in many ways, but usually involves the construction of numerous terraces and dams. It should be noted here that the large dams constructed for the purpose of generating hydroelectric power must be differentiated from those whose primary object is flood control. Lakes created for the former purpose are kept nearly full all the time and therefore can exert little effect in controlling floods in periods of excessive rainfall.

Because large dams are very expensive, the site for such a dam should be most carefully chosen and the geologic conditions thoroughly evaluated. Unfortunately, many large dams have been located without geological advice. One such dam in California was located directly across an active fault line. Other dams were built on rocks which were so badly fissured by jointing that much of the impounded water escaped. In still other instances solution cavities in the foundation rock or at the sides of the dam permitted the escape of water in large quantities. Some dams have been constructed across valleys where there never will be enough drainage to fill the basin created by the dam.

A geologic feature which is too often neglected in planning an artificial lake of large size is the rapid silting of a reservoir caused by the dropping of sediment as the current of the incoming stream is checked. Although this factor may be negligible in mountainous areas where streams are clear most of the time, it becomes very serious in those regions where the streams are muddy almost every day in the year.

This condition exists in large parts of many of the southern and southwestern states. Near Austin, Texas, a condition like this exists, and if silting continues at the rate noted in the first few years of the life of Lake Austin, the basin will be completely filled when it is fourteen years old.¹

Geologic factors also play an important part in highway engineering and construction. The cost of maintenance of most highways is determined to a large extent by the consideration given to the type of rock or soil upon which the road is built. Bridges which have been located without regard to geologic processes or foundation materials are very often rendered useless. Many years ago a bridge more than a half mile in length was constructed near Norman, Oklahoma, across a floodplain meander of the South Canadian River. This long bridge was left "high and dry" when the stream deserted its old channel to follow a new one around the end of the bridge.

Perhaps the greatest contribution geology makes to man is to teach him an appreciation of his surroundings. When we first learn that hills and valleys, lakes and streams, are not accidental and are not permanent features of our landscape, we began to understand and appreciate why one area is mountainous and another is a level plain. We can explain why in some sections of the country the water is hard although in nearby regions the water is soft. The difference between the rocky farms of much of New England and the swampy land of southern Louisiana is readily explained on the basis of the geologic processes which have affected each.

Such scenic features as the Grand Canyon, Niagara Falls, Rainbow Bridge, The Needles, Royal Gorge, the Matterhorn, and the host of others we visit or see pictured become even more interesting and fascinating as we understand those processes of nature which have brought them into existence. Each bit of travel brings us in contact with new and different features of the landscape, with a panorama which has been constantly changing for tens or even hundreds of millions of years. Differences in climate, elevation, character of rock, and other factors cause each large unit of the earth's surface to differ from every other region of similar size in the entire earth. An evaluation of these factors for every square mile of the continents is the pleasant task of the

¹H. M. Eakin and C. B. Brown, *Technical Bulletin 524*, United States Department of Agriculture, 1939.

geologist. The presence of minerals of economic value has caused some areas to be studied earlier and more intensively than other regions. Nor is the geologist content to study the land areas alone. Exploration of the ocean floor both for commercial and for strictly scientific purposes is now being carried on extensively, particularly on the shallower parts of the continental shelf.

The geologist is primarily an explorer. Every expedition to the continent of Antarctica has included a geologist in the personnel of the party. But exploration not only includes study and mapping of little-known places like Antarctica, northern Alaska, or northwestern Canada. It may also mean the examination of cuttings obtained in the drilling of deep wells, some of which have reached depths of more than three miles. A different kind of exploration is that carried on by geologists who identify and classify the microscopic fossils in a bit of rock or reconstruct the life of past periods of the earth's history from the larger fossils, such as those of the dinosaurs.

The field of the geologist is ever expanding. New uses are being discovered for well-known earth materials, thereby creating a need for greater exploration. The atomic bomb is now instituting in every nation an intense search for the minerals from which atomic power can most easily be obtained. This is but one instance in which a single mineral has profoundly affected the life of every person.

APPENDIX



A · BASIC FACTS ABOUT THE EARTH

1. *Area.* 196,950,284 square miles. Land area, approximately 57,510,000 square miles; water area, approximately 139,440,000 square miles.

2. *Dimensions.* Diameter, equator, 7926 miles; pole to pole, 7900 miles. Circumference, equatorial, 24,902 miles; through poles, 24,860 miles.

3. *Mass.* 6000 million million million tons.

4. *Density.* (Average) 5.527.

5. *Elevations.* Highest point measured, Mt. Everest, Nepal, India, 29,141 feet above sea level. Highest point in North America, Mt. McKinley, Alaska, 20,300 feet. Highest point in South America, Aconcagua, Argentina, 22,834 feet. Highest point in Europe, Mt. Elbrus, Soviet Union, 18,465 feet. Highest point in Africa, Mt. Kibo, British East Africa, 19,710 feet. Highest point in the United States, Mt. Whitney, California, 14,495 feet.

Lowest point in the United States, Death Valley, California, 280 feet below sea level. Lowest elevation of land surface of the world, Dead Sea, Palestine, 1290 feet below sea level.

Average elevations of the continents: North America, 2300 feet; South America, 3100 feet; Asia, 3300 feet; Europe, 1100 feet; Africa, 2200 feet; Australia, 700 feet; Antarctica, about 6000 feet.

6. *Ocean Depths.* Pacific, average, 14,050 feet; maximum known (near Mindanao, Philippines), 35,433 feet. Atlantic, average, 12,880 feet; maximum known (north of Puerto Rico), 30,246 feet. Indian, average, 13,000 feet; maximum known, 22,968 feet. Arctic, average, 3950 feet; maximum known, 17,850 feet. Antarctic, average, unknown; maximum known, 14,274 feet.

7. *Temperatures.* Maximum official, 136° at Azizia, North Africa. Maximum official, United States, 134° at Greenland Ranch, Death Valley, California.

Minimum (not officially confirmed), -94°, in Siberia. Minimum official, United States, -66°, in Yellowstone National Park.

8. *Precipitation.* Maximum rainfall, average, 426 inches annually, Cherra Punji, India. Maximum rainfall, United States, 150.73 inches, Wynoochee Oxbow, Washington.

Minimum rainfall, average annual precipitation of .04 inch is reported at Arica, Chile, and several stations in the Egyptian Sahara report even smaller amounts. Minimum rainfall, United States, 1.35 inches, at Greenland Ranch, California.

Heaviest rainfall, reported to have occurred at Baguio, Luzon, 46 inches in 24 hours, and at Cherra Punji, India, more than 150 inches in five days, 241 inches in one month.

9. *Wind Velocity.* Highest on record probably 231 miles per hour, on Mt. Washington, New Hampshire. Higher velocities occur in connection with tornadoes.

B · IMPORTANT ROCK-FORMING MINERALS

Mineral or Group	Composition	Characteristics	Remarks
Orthoclase Feldspars	KAlSi_3O_8	Usual colors: white, flesh pink, gray, red. Often breaks in two planes at right angles to each other. Too hard to be scratched by knife blade	The "potash feldspars," including <i>orthoclase</i> and <i>microcline</i> . These feldspars form in the presence of an excess of silica, and are almost always associated with quartz
Plagioclase Feldspars	$\text{NaAlSi}_3\text{O}_8$ and $\text{CaAl}_2\text{Si}_2\text{O}_8$	Usual colors similar to those of the orthoclase group; some forms darker. Hardness same as of orthoclases. Break in planes nearly although not quite at right angles. Most easily distinguished from orthoclase feldspars by presence of striations on some cleavage faces	The "soda-lime feldspars," comprising a series from <i>albite</i> , $\text{NaAlSi}_3\text{O}_8$, to <i>anorthite</i> , $\text{CaAl}_2\text{Si}_2\text{O}_8$, the intermediate members, <i>oligoclase</i> , <i>andesine</i> , <i>labradorite</i> , and <i>bytownite</i> , being mixtures of the two extreme members. Silica is less abundant than in the foregoing groups, and decreases in the plagioclase series from albite to anorthite
Muscovite	$\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$	Usual colors: gray, yellowish, brownish. Can be scratched by fingernail. Splits into very thin, lustrous, flexible sheets	<i>Muscovite</i> , <i>biotite</i> , and a number of less common silicates of similar composition constitute the mica group
Biotite	$\text{K}(\text{Mg, Fe})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	Similar to muscovite, but black, dark brown, or green in color	
Olivine	$(\text{Mg, Fe})_2\text{SiO}_4$	Usual color: green. Hardness greater than that of orthoclase, approaching that of quartz. Commonly granular, occurring either in masses or as scattered grains	
Amphibole	Complex silicate group of variable composition. Contains magnesium, usually calcium, often iron	Usual colors: black, gray, green. Hardness about equal to that of a knife blade	<i>Hornblende</i> , a very common rock-forming mineral, is the most abundant member of the group
Pyroxene	Complex silicate group of variable composition resembling that of amphibole	Closely resembles the amphiboles in most characteristics	<i>Augite</i> is the best-known example. Common in many igneous rocks
Quartz	SiO_2	Color: extremely variable. Harder than steel, will scratch orthoclase. Usually breaks along slightly curved surfaces	In conspicuous crystals, or in masses of microscopic crystals. <i>Opal</i> is a noncrystalline variety containing variable quantities of water

C · COMMON ROCKS

IGNEOUS ROCKS

Name		Silica	Typical Feldspars	Typical Ferromag- nesian Minerals	Remarks
Phanerite Group	Aphanite Group				
Granite	Rhyolite	Free quartz/ present	Orthoclase	Biotite, hornblende (subordinate to feldspars)	Light-colored
Syenite	Trachyte	Little or no free quartz	Orthoclase	Biotite, hornblende	Light-colored
Diorite	Andesite	Reduced in amount	Plagioclases, especially those of sodium	Hornblende	Commonly gray or green. Some authorities base distinction between diorite-andesite and gabbro-basalt groups upon kind of ferromag- nesian minerals present, others upon kind of feldspars
Gabbro	Basalt	Relatively less than in fore- going groups	Plagioclases, especially those of calcium	Pyroxenes, usually with some olivine; in most cases about equal to feldspars in amount	Dark in color
Peridotite	Basalt (trap), see remarks	Little or none	Absent, or nearly so	Olivine, pyroxene	Basalt in this sense is a general name for rocks of this kind. Peridotite may be used similarly to include pyroxenite and dunite

SEDIMENTARY ROCKS

Name	Origin	Characteristics
Conglomerate	Clastic	Rounded pebbles of any kind cemented by matrix, usually siliceous
Breccia	Clastic	Angular pebbles similarly cemented
Sandstone	Clastic	Sand grains, usually of quartz, cemented by various substances, such as iron oxide or hydroxide, calcium carbonate, or silica

Name	Origin	Characteristics
Arkose	Clastic	Chiefly feldspar and quartz, as from imperfectly disintegrated granite
Shale	Clastic	Indurated mud or clay
Limestone	Clastic, chemical, or organic	Largely calcium carbonate, deposited as very fine clastic grains, whole or fragmental shells, or precipitated from solution
Coquina	Organic	Variety of limestone, consisting of calcareous shells or shell fragments
Chalk	Organic	Variety of limestone, usually composed of microscopic shells of calcium carbonate
Travertine	Chemical precipitate	Variety of limestone deposited by spring or river water, or in caves in the form of stalactites and stalagmites
Oolite	Chemical precipitate	Mass of small spherical grains, of either calcium carbonate or silica
Rock salt	Chemical precipitate	Sodium chloride, usually deposited by evaporating waters
Gypsum	Chemical precipitate	Calcium sulfate and water, deposited by evaporating waters
Coal, bituminous	Organic	Carbonized plant remains

METAMORPHIC ROCKS

Name	Original Form	Characteristics
Gneiss	Granite, conglomerate, or other rock	Coarsely banded; contains feldspar, quartz, and dark minerals
Schist	Almost any igneous or sedimentary rock	Finely banded or foliated; grains of intermediate size; may contain much mica, chlorite, hornblende, or other silicate, but little feldspar
Phyllite	Shale or other rock	Fine-grained, intermediate between schist and slate
Slate	Shale or other rock	Very fine-grained, with perfect secondary cleavage
Marble	Limestone	Coarse-grained, because of recrystallization
Quartzite	Sandstone	Quartz grains cemented by silica, breaking along smooth surfaces

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SECTIONS OF TOPOGRAPHIC MAPS

Many topographic features, especially those whose meaning must be gleaned from a broad areal view, can be studied more advantageously from topographic maps than from either photographs or diagrams. The following pages contain portions of a number of maps, selected for their usefulness in illustrating geological principles, as well as for giving the reader some familiarity with this type of map.

The elevation of any desired point on a topographic map can be determined, at least approximately, by means of *contour lines*, which are shown in brown. A contour line is a line every point of which is at the same elevation above mean sea level. The *contour interval*, which is indicated at the bottom of the map, is the vertical distance in feet between adjacent contour lines of different elevations. The contour interval is different for different maps because the regions involved differ in relief and in practical importance. The contour intervals usually employed are 5, 10, 20, 25, 50, and 100 feet.

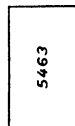
Especially heavy brown lines represent elevations which are certain multiples of the contour interval; these lines, unless too short, will be found to bear a number indicating their elevation in one or more places. To get the elevation of any contour line, then, one needs only to find the nearest heavy line and count up or down to the desired point, allowing one contour interval for each line crossed. In case of doubt as to the direction in which the land slopes, one or more of the following points will generally be found sufficient to eliminate the difficulty: (1) if contour lines (except depression contours) completely close upon themselves within the area of the map, they always enclose areas of higher ground; (2) where contour lines cross stream valleys, they always bend upstream; (3) the junction of tributaries with their main streams usually forms an acute angle facing upstream. For example, the map of Weedsport, New York, on page 449 depicts a group of hills indicated by elliptical contour lines, each of which represents an elevation 20 feet higher than that of the line outside it. On the map of Edmond, Oklahoma, on page 440 we note that contour lines crossing the tributaries of Deep Fork do not cross at right angles, but that they always bend upstream—that is, toward higher ground. The acute angles made by the union of these streams are also plainly in evidence.

For determining horizontal distances, the scale of the map must be known. The scale, also indicated at the bottom, is expressed as a fraction representing the ratio between distances on the map and corresponding distances on the ground. Thus a scale of 1/100 would mean that one unit on the map represents 100 similar units on the earth's surface. The scales most commonly used on maps of this type are 1/62,500 and 1/125,000, which are practically equivalent to one mile to the inch and two miles to the inch respectively.

Topographic maps are printed in three or more colors. Relief features are shown in brown, bodies of water in blue, and works of man (as well as lettering and boundaries) in black. On some maps wooded areas are shown in green, and on some certain roads are indicated in red. On the two following pages are the standard symbols employed on topographic maps. Examples of such maps occur on pages 435–450.

RELIEF

(printed in brown)



Elevation above mean sea level
(in black on recent maps)



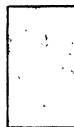
Contours
(Contours showing depth of water printed in blue)



Depression contours



Levee



Wash



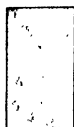
Cliffs



Mine dumps



Tailings or mining debris



Sand and sand dunes

WATER

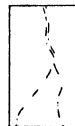
(printed in blue)



Streams



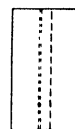
Falls and rapids



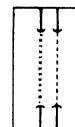
Intermittent streams and ditches



Canals or ditches



Aqueducts or waterpipes



Aqueduct tunnels



Lake or pond



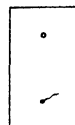
Unsurveyed stream and abandoned canal



Intermittent lake



Glacier
(Or shown by contours printed in blue)



Spring Well

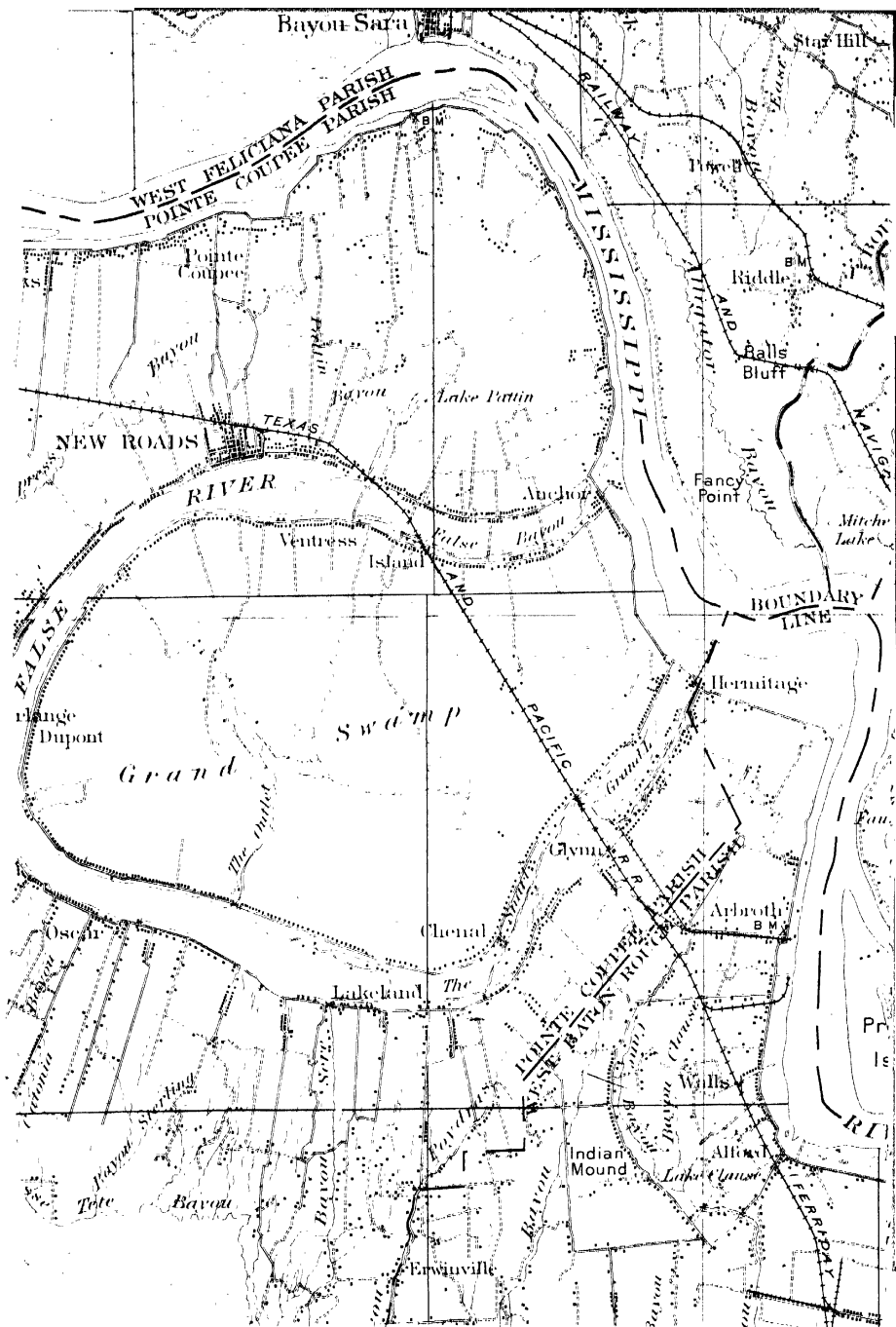


Marsh



Submerged marsh

City or village	Roads and buildings	Ruins	Cliff dwelling	Good Public road	Poor Public or private road	Trail	Railroads	Electric railroad
Tunnel	Power-transmission line	Wharves	Breakwater and jetties	Bridge	Drawbridges	Ferry (point upstream)		
Ford	Dam	Dam with lock	Canal lock	U.S. township and section lines and recovered corners	State line	County line		
Civil Township or district line	Reservation line	Land and grant line	City, village, or borough line	Small park or cemetery line	Triangulation point or transit traverse station	U.S. mineral monument		
Boundary monument (supplementary bench mark shown by cross and black figures without lettering)	Bench mark	Cemeteries	Church, School (distinguished on recent maps)	Coke ovens	Tanks and oil reservoirs	Oil and gas wells		
Mine or quarry	Prospect	Shaft	Mine tunnel	Mine tunnel (showing direction)	Lighthouse or beacon	Coast Guard station		



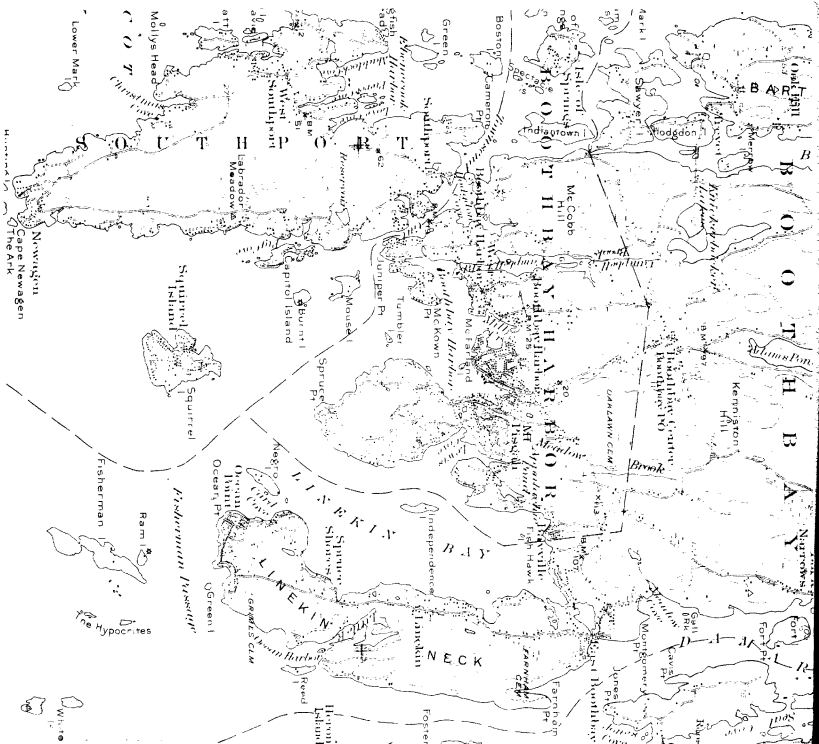
Scale $\frac{1}{125000}$
 0 1 2 3 4 Miles
 Contour interval 20 feet.

435

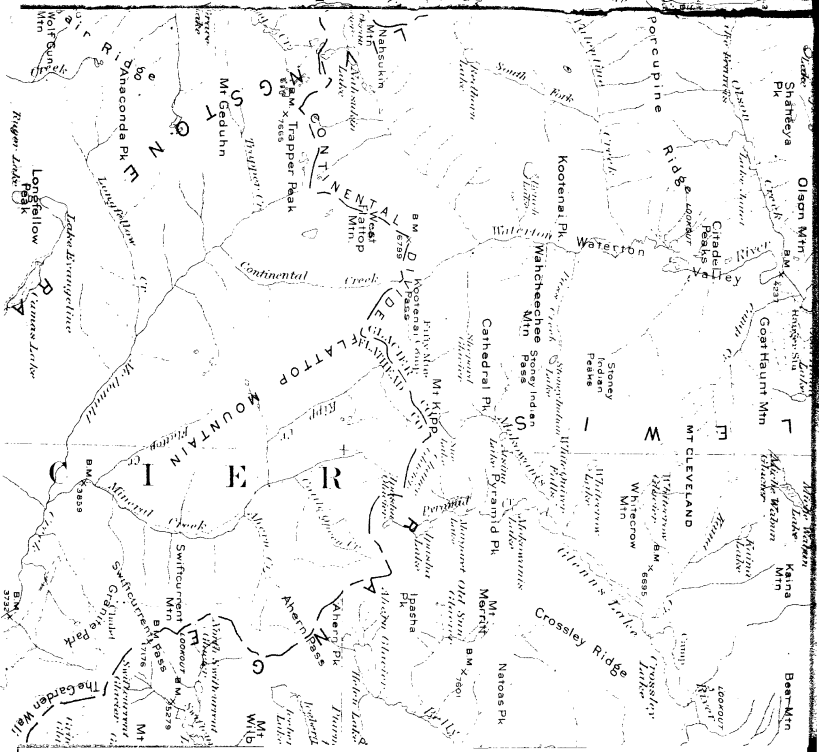
Section of Bayou Sara,
 Louisiana Map

Section of Boothbay,
Maine Map

Scale 436 0 3 Miles
Contour interval 20 feet

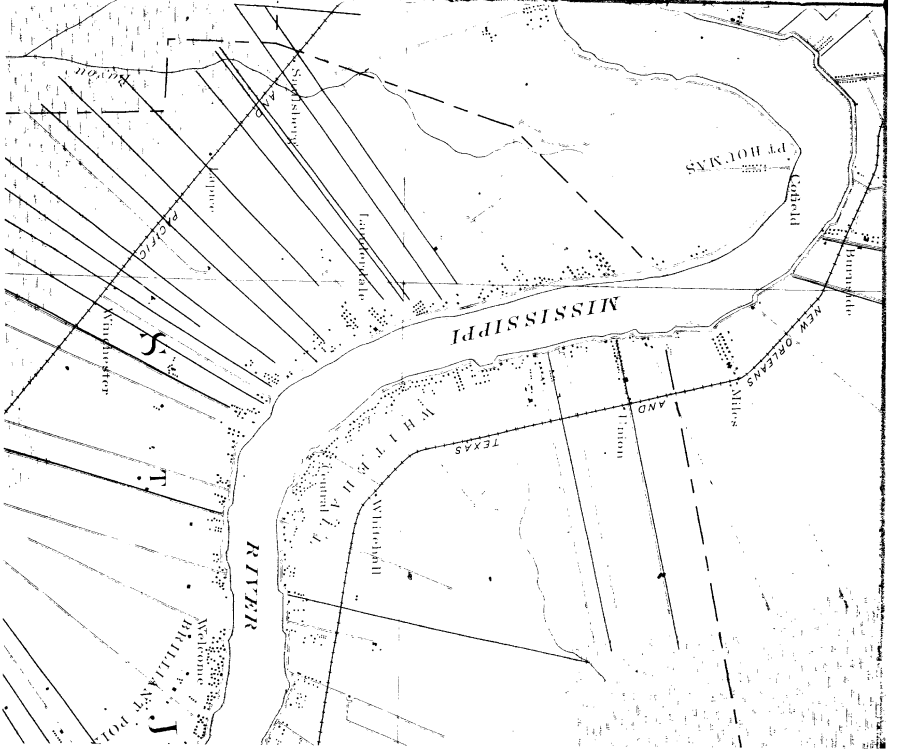
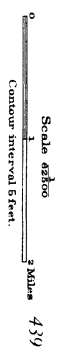
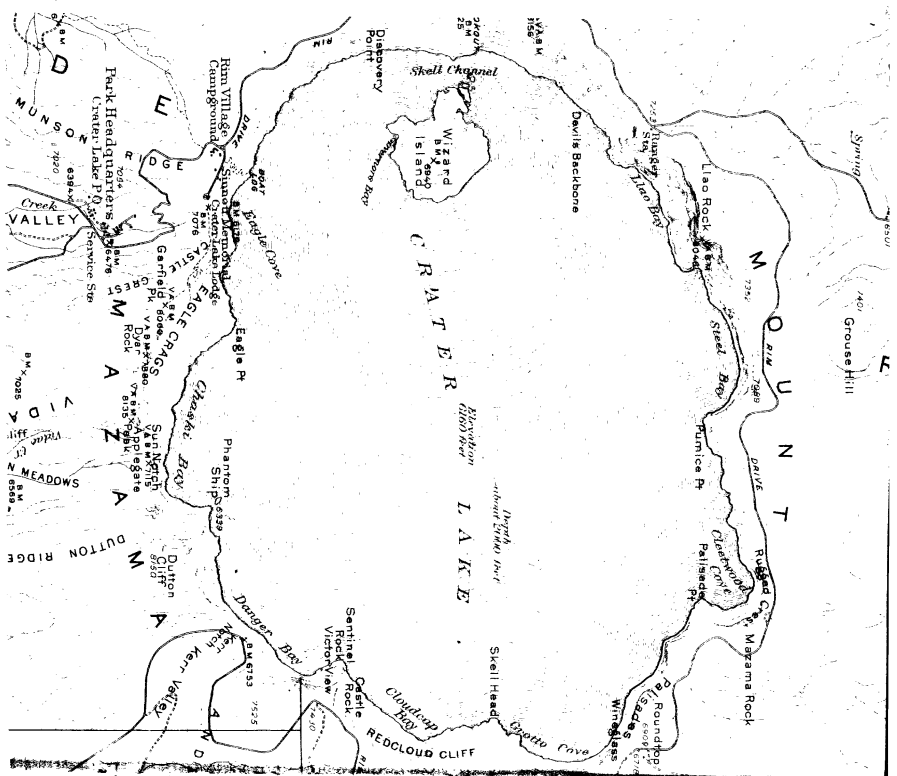
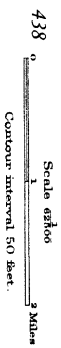


Scale 437 0 3 Miles
Contour interval 100 feet

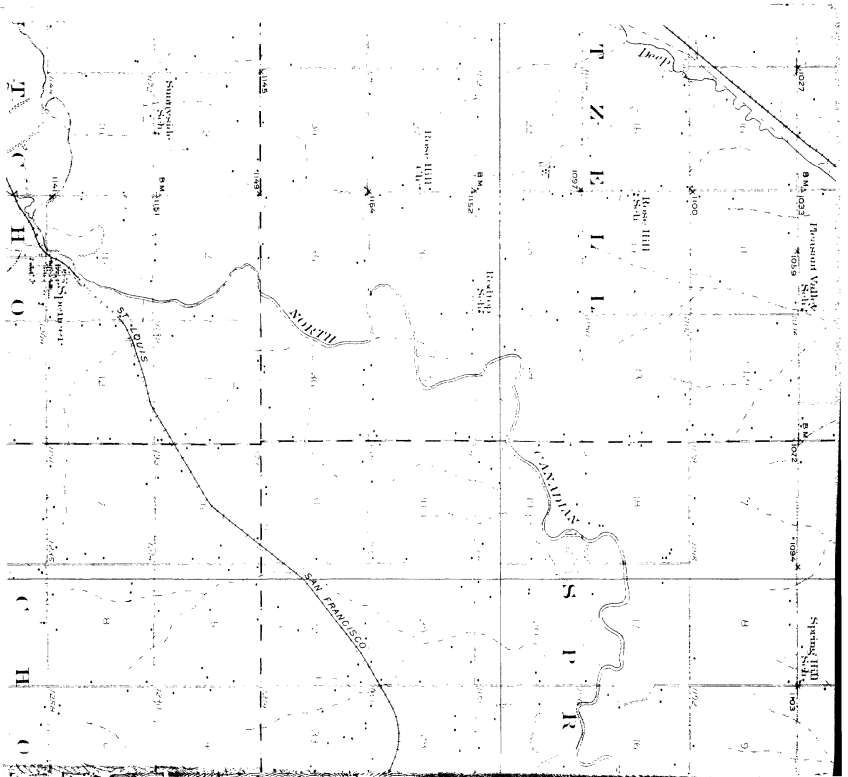
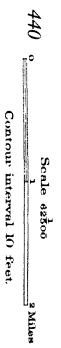


Section of Carat Mountain,
Maine Map

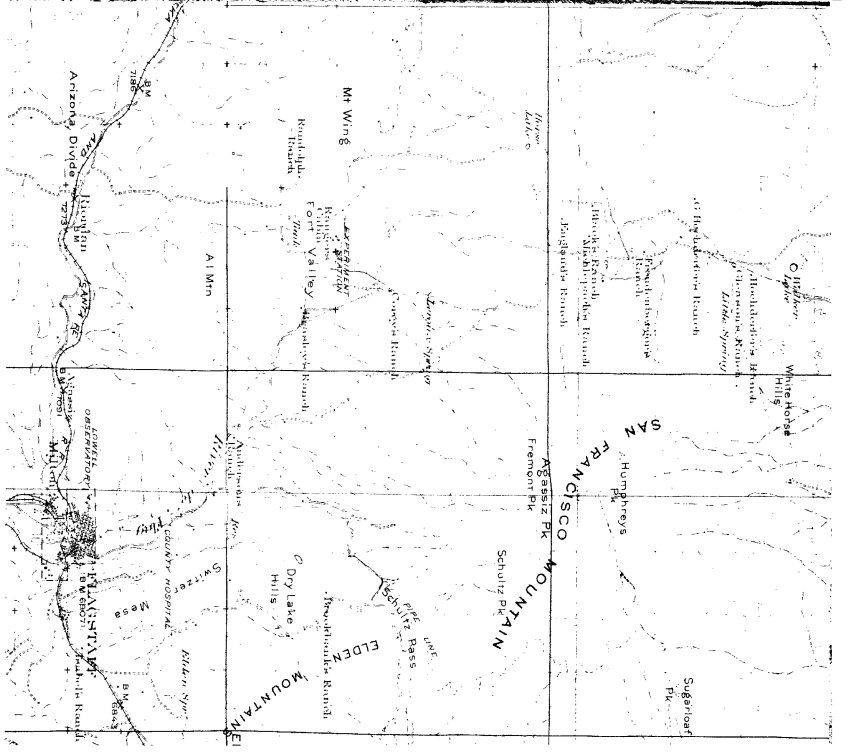
Section of Crater Lake National Park,
Oregon Map

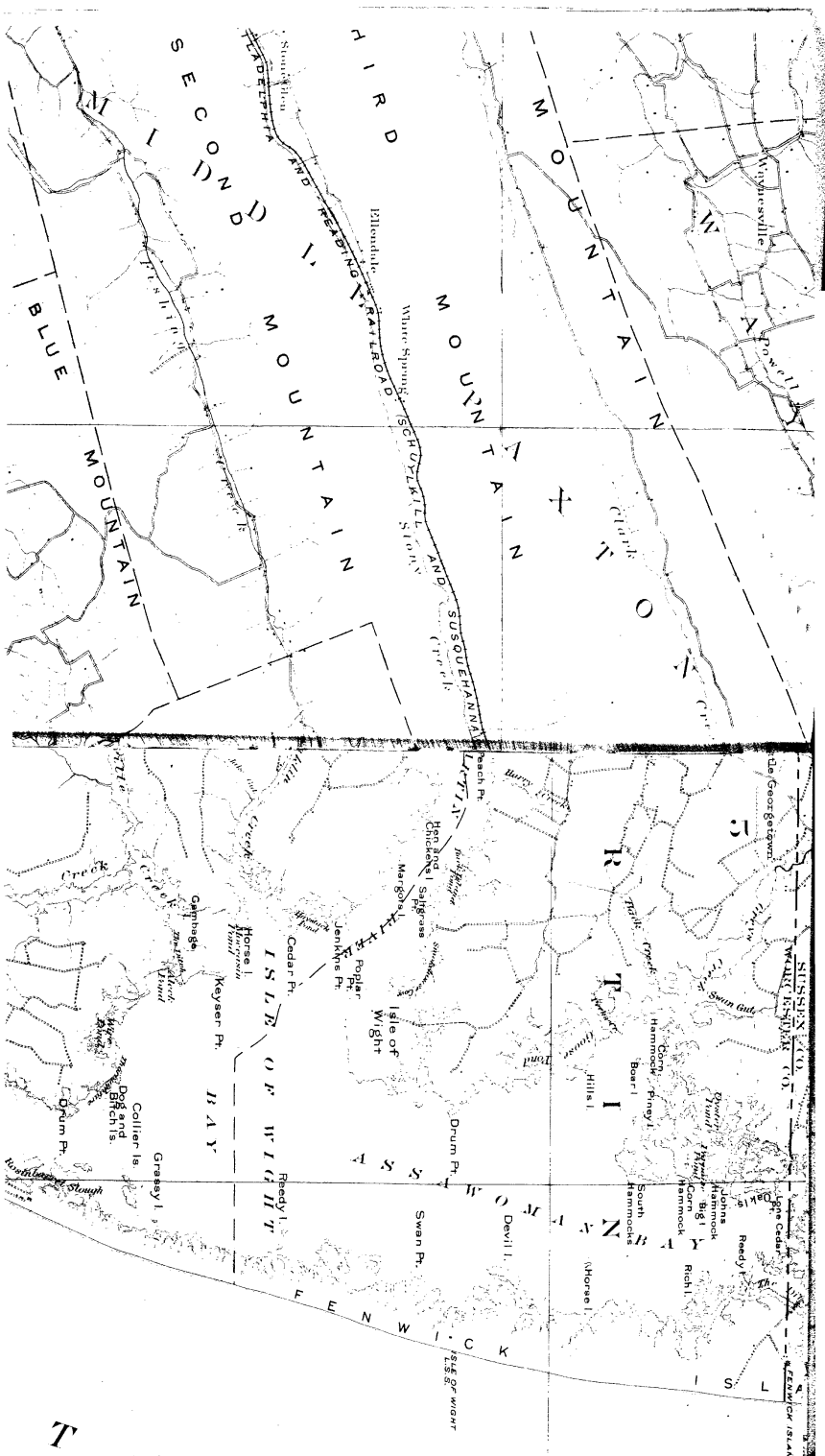
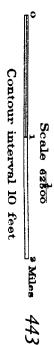
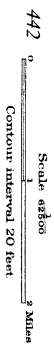
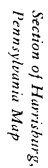


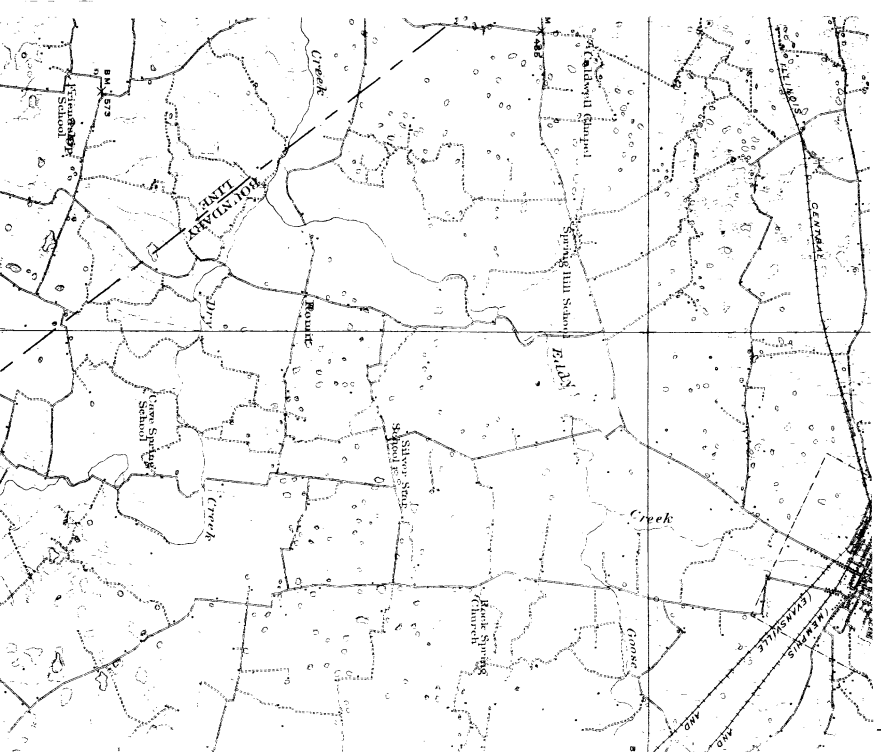
Section of Edmond,
Oklahoma Map



Section of Flagstaff,
Arizona Map

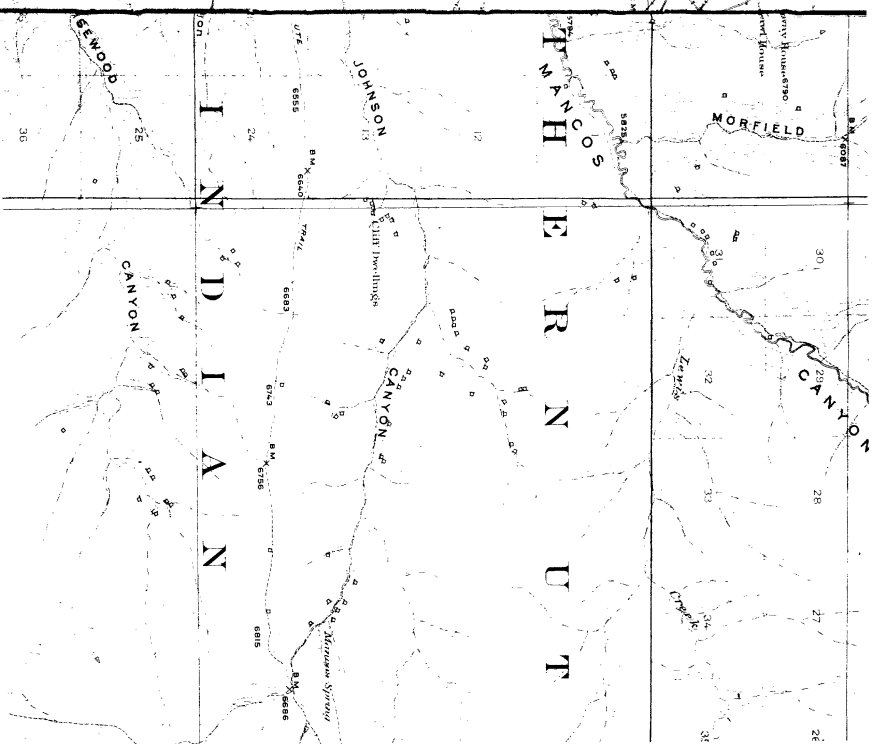






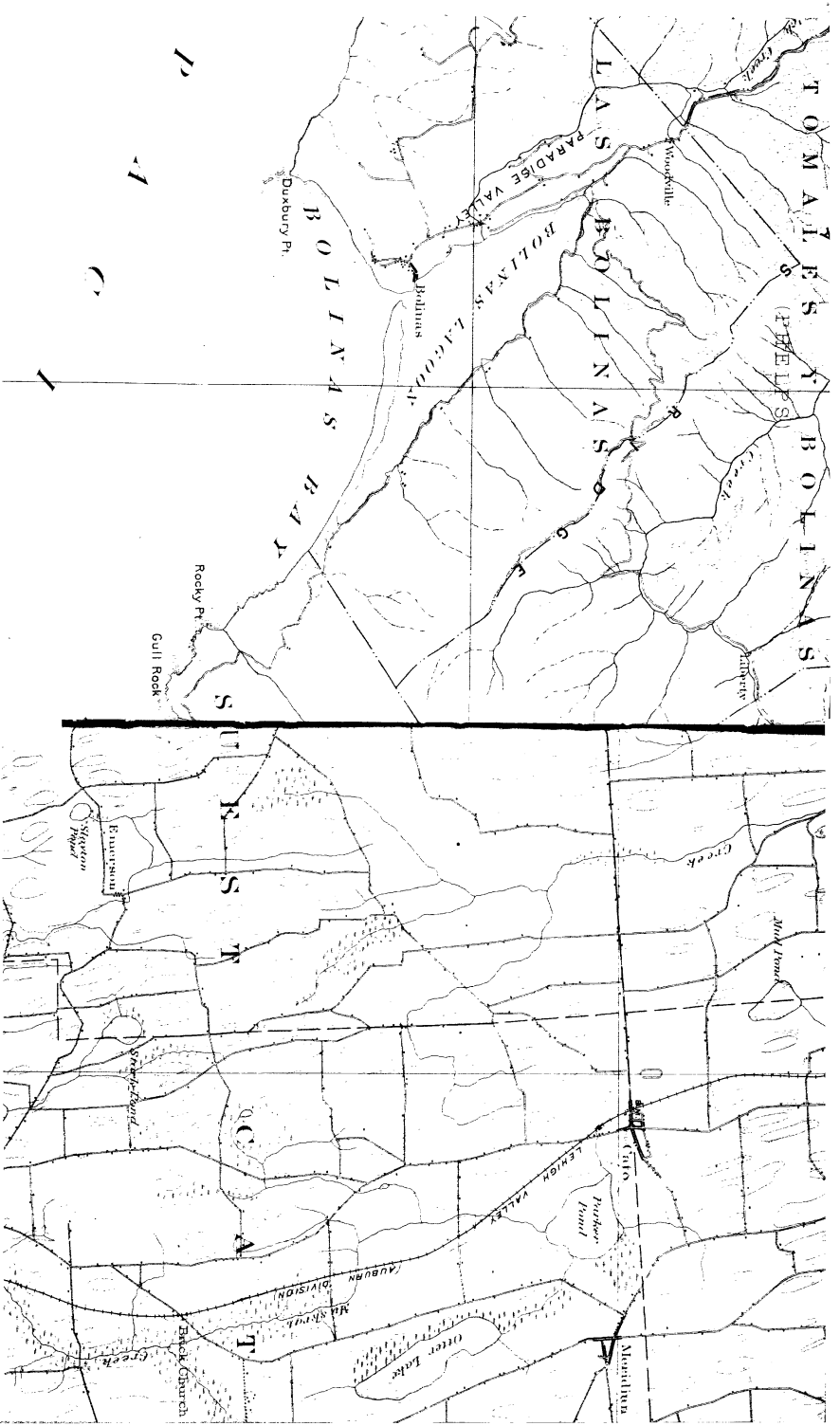
Section of Princeton,
Kentucky Map

Scale 446
0 1 Mile
Contour interval 20 feet



Scale 447
0 1 Mile
Contour interval 50 feet

Section of Soda Canyon,
Colorado Map

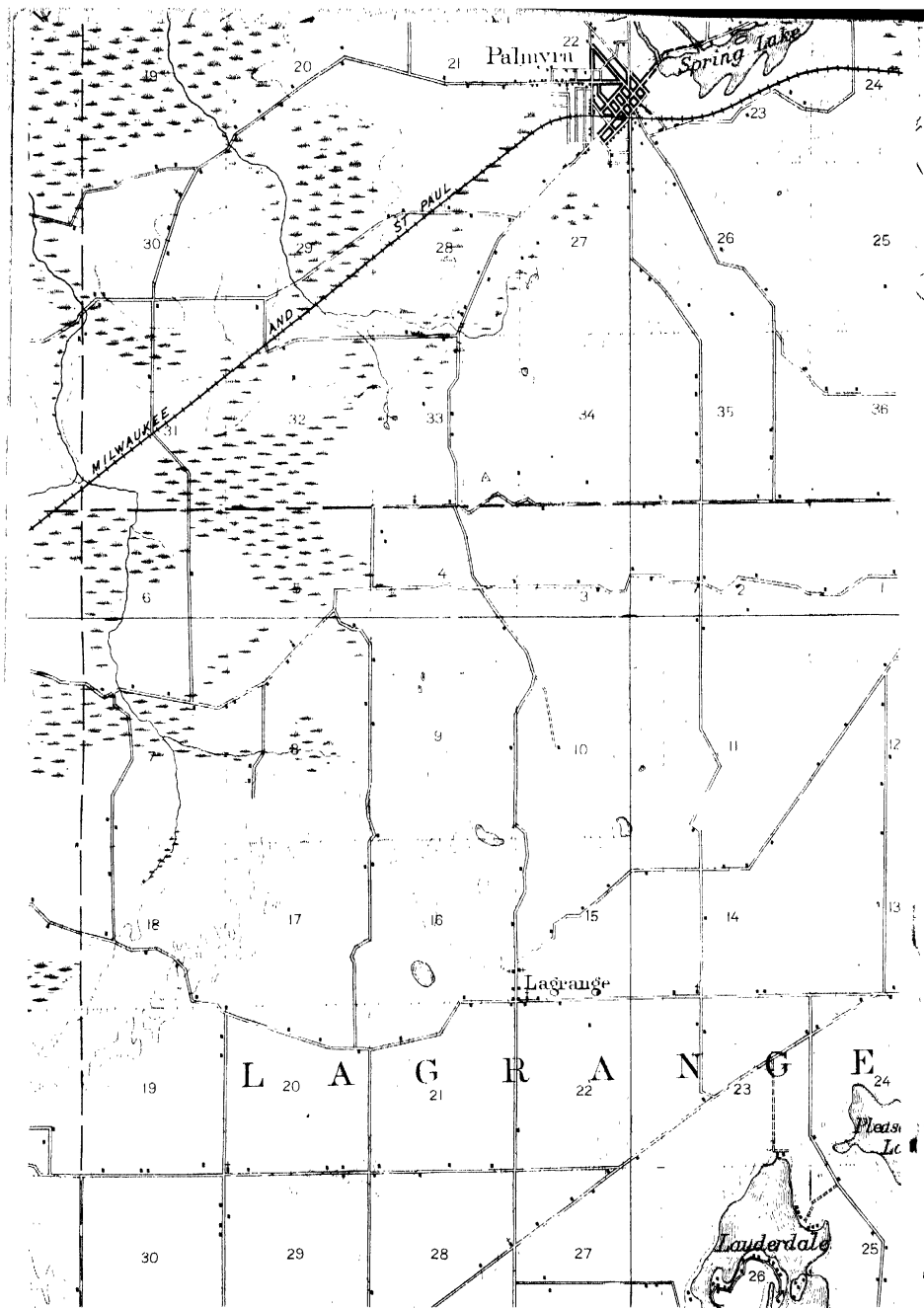


Section of Tomalpais,
California Map

448 0 Scale 6800 3 Miles
Contour Interval 25 feet.

0 Scale 6800 3 Miles 449
Contour Interval 20 feet

Section of Wecaport,
New York Map



Section of Whitewater,
Wisconsin Map

450

Scale 62500

1 2 Miles

Contour interval 20 feet

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